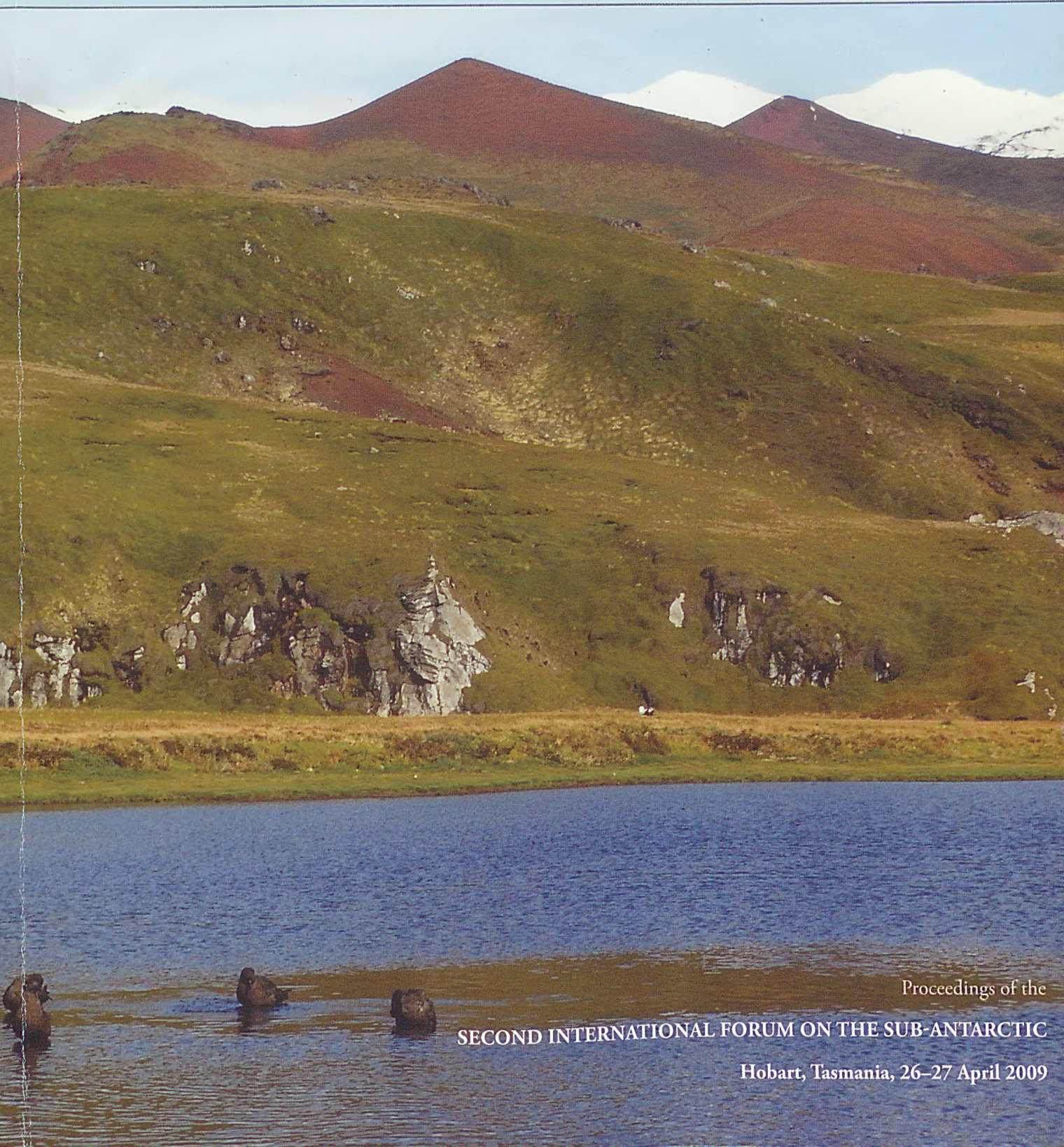


ENVIRONMENTAL CHANGE IN THE SUB-ANTARCTIC

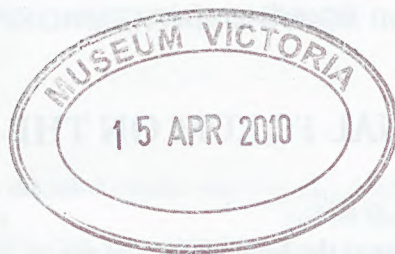
Edited by Margaret Davies,
Patrick G. Quilty and Patricia M. Selkirk



Proceedings of the
SECOND INTERNATIONAL FORUM ON THE SUB-ANTARCTIC

Hobart, Tasmania, 26–27 April 2009





PAPERS AND PROCEEDINGS OF

THE

ROYAL

SOCIETY

OF TASMANIA



Edited by Margaret Davies,
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Convention for the Conservation of Antarctic Marine Living Resources, Hobart, Tasmania

26–27 April 2009

Organised by a Steering Committee

Sir Guy Green (Chair), Honorary Antarctic Ambassador for Tasmania
Ben Galbraith, formerly Director, Antarctic Tasmania
Professor Bruce Mapstone, CEO Antarctic Climate and Ecosystems CRC
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Dr Patricia Selkirk, Senior Research Fellow, Macquarie University
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on behalf of

Antarctic Tasmania



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Cover photo: Prinsloomeer, Marion Island. Kindly provided by Dr Herbert Dartnall.

*Statements of opinions expressed in papers in this volume reflect the views of the author(s)
and are not necessarily those of the Royal Society of Tasmania.*

PREFACE: ENVIRONMENTAL CHANGE IN THE SUB-ANTARCTIC

The second International Forum on the sub-Antarctic was held in Hobart on 26–27 April 2009.

The first Forum, held in Hobart on 6–7 July 2006, considered the characteristics and unique features of the sub-Antarctic islands, ocean and atmosphere, and examined conservation and management of the sub-Antarctic islands and ocean by both national and international bodies. Its proceedings were published in November 2007 as Volume 141(1) of the *Papers and Proceedings of the Royal Society of Tasmania*. Following the success of the first International Forum on the sub-Antarctic, it was agreed that further meetings would be held, ideally on a biennial basis.

At the second Forum, the focus was on environmental change in the sub-Antarctic. Over the course of two days, speakers and ensuing discussion addressed change over various time periods, and in various components of the sub-Antarctic system:

- How the sub-Antarctic environment and system came to be, how it works and how it has changed from its beginning to the coming of humans
- Change in the sub-Antarctic system during the recent past, circa 1800 to mid-twentieth century
- Change in the modern era of science and environmental consciousness
- Dynamic interactions in the sub-Antarctic system — atmosphere, water and land
- Managing and adapting to environmental and ecological change.

We thank all those who helped with organising the Forum, and all those who participated — speakers, presenters of posters concerning current research, audiences and those who contributed to discussions. We are grateful to those who assisted with this publication by acting as reviewers for the manuscripts.

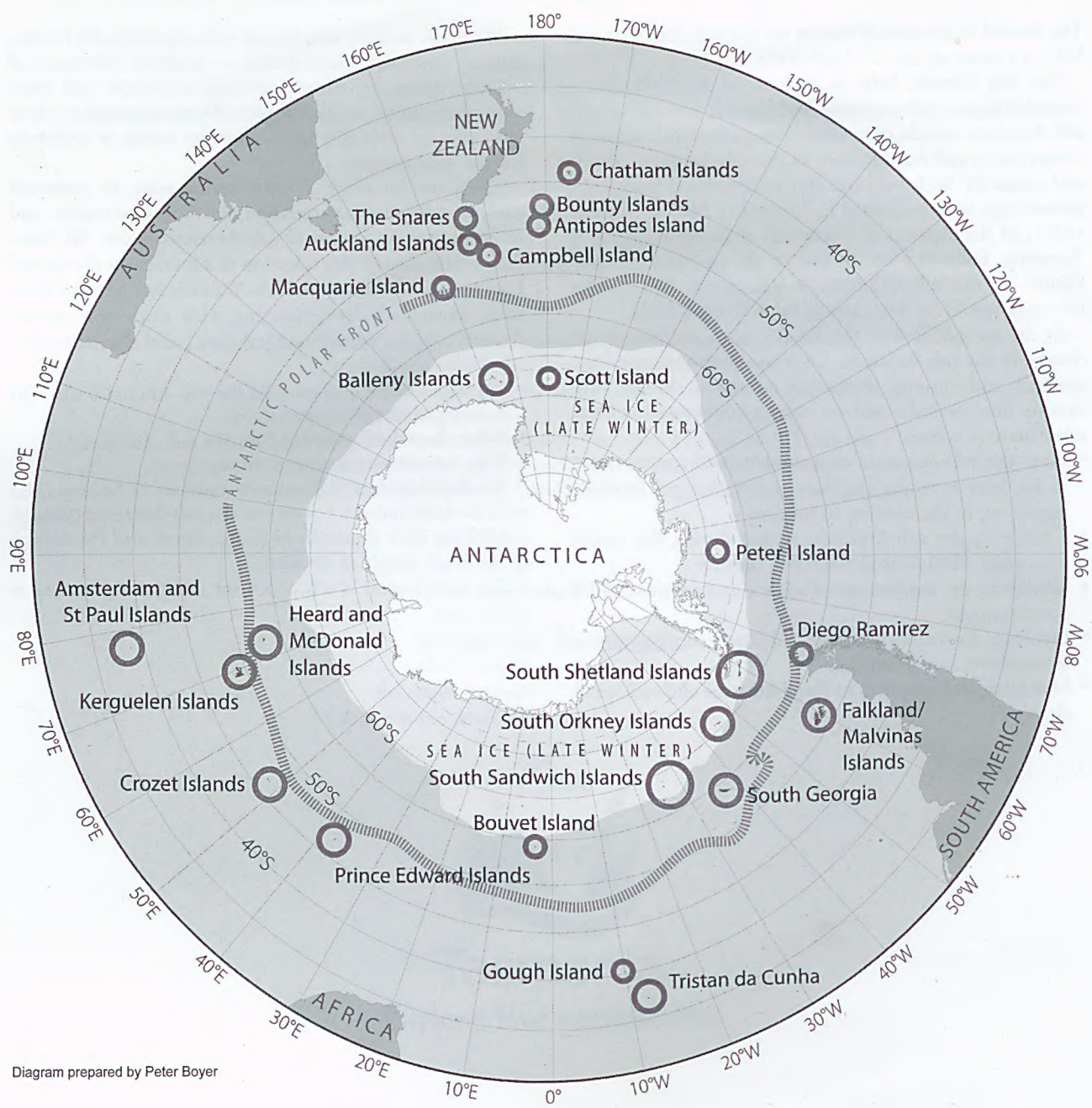
The Sub-Antarctic Forum series aims to promote understanding and appreciation of this unique region, and to encourage discussion of sub-Antarctic issues. We hope that publication of this selection of papers from the second International Forum on the sub-Antarctic will advance these aims, particularly by promoting wide discussion around the topics of the *Mirror on the Future* panel discussion that concluded the Forum:

- The significance and value of the sub-Antarctic and why it is important to understand it
- What does the future hold for the sub-Antarctic?
- Why considering its future is important.

The Royal Society of Tasmania is pleased to be associated with the International Forums on the sub-Antarctic through publishing their proceedings in the *Papers and Proceedings of the Royal Society of Tasmania*.

The next Forum is scheduled for 2011 and planning is under way.

Margaret Davies
Patrick G. Quilty and
Patricia M. Selkirk (co-editors)



PAPERS AND PROCEEDINGS OF THE ROYAL SOCIETY OF TASMANIA

VOLUME 143, PART 1

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CLIMATE TRENDS AT MACQUARIE ISLAND AND EXPECTATIONS OF FUTURE CLIMATE CHANGE IN THE SUB-ANTARCTIC

by Neil Adams

(with 11 text-figures)

Adams, N. 2009 (11:xi): Climate trends at Macquarie Island and expectations of future climate change in the sub-Antarctic. *Papers and Proceedings of the Royal Society of Tasmania* 143(1): 1–8. ISSN 0080-4703. Bureau of Meteorology, GPO Box 727, Hobart, Tasmania 7001, Australia. Email: N.Adams@bom.gov.au

Macquarie Island has experienced a marked shift in its climate since 1970, with increasing precipitation, accompanied by a steady increase in mean wind speed associated with increased cyclonic activity. These trends are consistent with an increase in the Southern Annular Mode (SAM) index, albeit with a shift to an anomalous atmospheric trough over the western Pacific Ocean. However, our understanding of the twentieth-century climate across the entire sub-Antarctic is limited by very sparse data and the relatively poor quality of global re-analyses across the Southern Hemisphere. Chapter 10 of the Inter-governmental Panel on Climate Change (IPCC) fourth Assessment Report (AR4) provides an assessment of global atmospheric trends out to the end of the twenty-first century and provides some clues as to the regional trends expected across the sub-Antarctic. This paper provides a synopsis of the changes experienced at Macquarie Island, and a look to future trends, and the need for increased atmospheric research in the mid- to high latitudes of the Southern Hemisphere.

Key Words: climate, climate change, Macquarie Island, sub-Antarctic.

INTRODUCTION

Variability and change in the weather and climate of the sub-Antarctic have received very little attention in the scientific literature. This region of the Southern Hemisphere has its southern boundary near the Antarctic convergence and a somewhat arbitrary northern boundary around 40°S. Pendlebury & Barnes-Keoghan (2007) provided a very good synopsis of the climate and climate change science in the sub-Antarctic but highlighted the very real need for more research. Fyfe (2003) in his modelling study on extra-tropical cyclones in the Southern Hemisphere concluded that the number of cyclones in the sub-Antarctic oceans has been decreasing over the past 50 years, and is projected out to 2100 to continue decreasing, with a continued drying and warming trend for the sub-Antarctic. Chapter 10 of the Inter-governmental Panel on Climate Change (IPCC) fourth Assessment Report (IPCC AR4) (IPCC 2007) also highlighted a significant warming trend across the sub-Antarctic over all seasons. However, precipitation changes were both regionally and seasonally more complex than suggested by Fyfe (2003), with a reduction in sub-Antarctic precipitation limited to more northern latitudes during summer, with winter precipitation generally increasing over most of the sub-Antarctic and in particular in the longitudes of Macquarie Island. One of the problems in drawing conclusions from such broad-scale modelling studies is that the sub-Antarctic spans all longitudes and regional trends may vary significantly. This is compounded by a key limiting factor in the number of long-term meteorological datasets available

to monitor the sub-Antarctic climate. Figure 1 shows the sparse network of stations dotted across the islands of the sub-Antarctic, and highlights the complete lack of observational sites directly south of the Australian mainland.

Of the two Australian sub-Antarctic islands, only Macquarie Island has an unbroken meteorological record that stretches back to 1948, whereas the record for Heard Island is discontinuous, with the bulk of observations limited to surface pressure and temperature. However, the Macquarie Island record offers a wealth of information from which to make comment on climate variability and change on the island and place these in the context of changes within the entire sub-Antarctic region. Furthermore the Macquarie Island weather record is a valuable quantum of

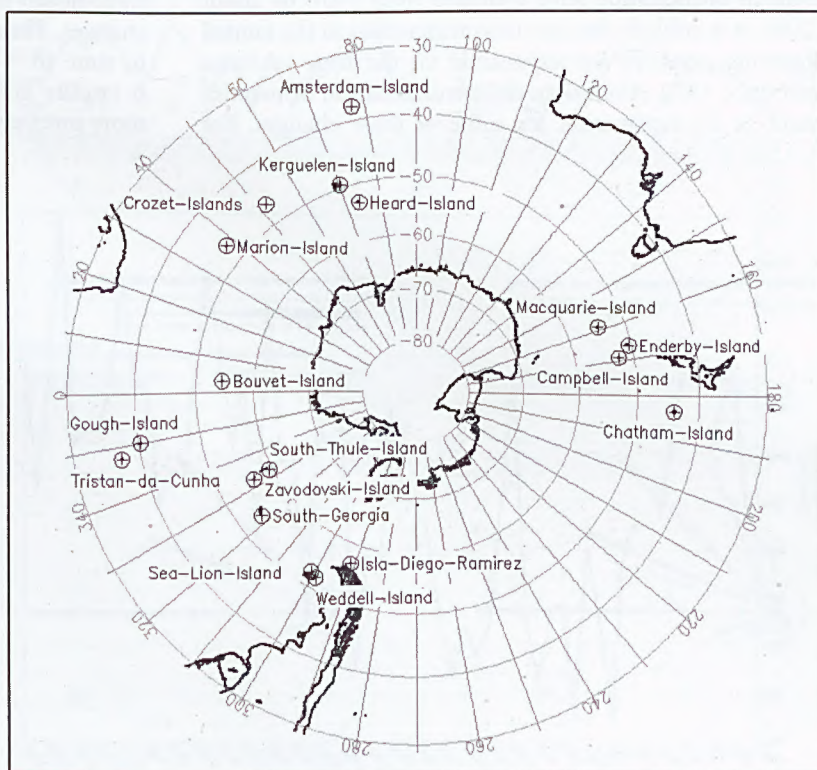


FIG. 1 — Sub-Antarctic stations reporting meteorological data.

information with which to better understand broad-scale changes seen in the biota of the island itself. Figure 2 shows the annual precipitation totals over the 60-year period from the beginning of records in 1948. In the first two decades of the record a clear reduction in precipitation was observed, followed by a steady and marked increase from around 1970 to the present day, with annual totals over the past decade exceeding those from the beginning of the record. This paper presents an analysis of the meteorological record from Macquarie Island over the 38 years since 1970, places the observed changes within the context of the broader scale changes seen in the sub-Antarctic, and provides a synopsis of some current research into expected changes out to the end of the twenty-first century.

THE MACQUARIE ISLAND RECORD

The most striking feature of the Macquarie Island meteorological record is the large change in observed rainfall since 1970. Over the 38 years since then there has been a steady increase in the annual total from around 800 mm/a in the very early 1970s, to around 1080 mm/a averaged over the past several years, as highlighted in the top panel of figure 3. The steady increase since 1970 amounts to about a 35% increase in precipitation. This striking change is not mirrored in the other meteorological records, with means in the near-surface wind speed, air temperature, dew-point and surface pressure (lower panels in fig. 3) not showing such striking changes. The wind speed record in figure 3 does show a slight increasing trend, and the dew-point has decreased slightly over the record, as has surface pressure, but these changes are subtle and confound any clear explanation of meteorological changes that would explain the dramatic increase in precipitation.

A seasonal breakdown of the meteorological data shows subtle increases in summer (9%), autumn (20%) and spring (28%) precipitation totals, but with a 55% increase in winter-time precipitation since 1970. August monthly totals in precipitation have increased from 1970 by about 120%. It is unlikely that any inhomogeneities in the rainfall observing practices are responsible for the large increases seen since 1970. Alterations in instrumentation or practice could be an explanation for some of these changes. For

example, in 1995 a snowfall recorder was installed on the island to catch snowfall that overflowed the rainfall recorder. However, it is unlikely that this additional amount of measured precipitation would be large, and there is no obvious signal in the rainfall record around this time. Other possible inhomogeneities are still under investigation (Ian Barnes-Keogh pers. comm.) but it is not expected that any changes in the rainfall recording are likely to be responsible for the observed increases.

Clearly, the precipitation record has been markedly influenced by changes in the winter-time weather. Figure 4 highlights the August rainfall totals since 1970, together with the mean monthly surface weather variables. The precipitation time-series shows a clear step change just after 1980 and a steady increase thereafter. Apart from a subtle increase in mean wind speed, and a decrease in surface pressure, no striking meteorological changes are apparent in the remaining surface weather variables. However, a more careful analysis of the near surface (10 m) wind record highlights differences between the pre-1982 and post-1982 climate. Figure 5a shows the wind-rose analysis for both periods, with the 1982–2008 data in pale grey overlaying the 1970–81 record in black.

There are two aspects of the wind-rose diagrams that are of note. First, the number of observations of northwesterly wind has decreased, the number of observations of a strong ($10\text{--}20\text{ ms}^{-1}$) north to northwesterly wind has increased, and the number of calm days has decreased. The changes in the number of calm days and north to northwesterly flow is even more marked when the 1982–2008 period is compared with the earlier records from 1948–69 (fig. 5b). The reduction in the number of calm days at the island would partly explain the increasing mean wind speeds (figs 3, 4), as would the increases in the strong north to northwesterly flow. Furthermore, the increasing north to northwesterly flow is indicative of a more meridional pattern and suggestive of more active rain-bearing frontal systems sweeping up to the island.

To further investigate cyclonic activity at the island the three-hourly surface pressure record was analysed for cyclonic changes. The second derivative of the pressure with respect to time ($\delta = d^2\text{slp}/dt^2$) was analysed. A positive value of δ implies falling pressure followed by rising pressure, or more precisely a low pressure event passing the island. The

number of these events exceeding threshold values was counted for each month. Figure 6 shows the monthly counts for $\delta = 0.2\text{ hPa/h}^2$ (a moderate change), and $\delta = 0.4\text{ hPa/h}^2$ (a strong change), for the period January 1970 to December 2008, with the annual means overlaid on the charts (thicker lines). A clear upward trend in the number of moderate changes crossing the island has occurred, with an increase from around 10 events per month to nearly 15 per month. With the strong events, there is a subtle increase from around two events per month to just under three. Clearly the inference from the Macquarie Island wind



FIG. 2 — Annual total precipitation for Macquarie Island for the period 1948–2008.

FIG. 3 — The Macquarie Island meteorological record for the period 1970–2008, with annual total precipitation (top panel), annual mean wind speed (second panel), annual mean temperature and dew-point temperature (third panel) and annual mean surface level pressure (bottom panel).

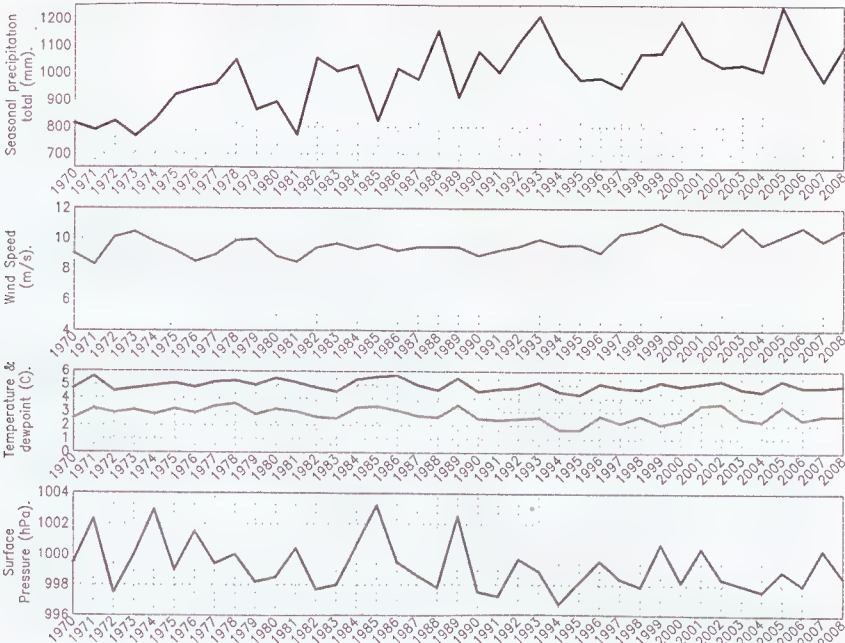


FIG. 4 — The Macquarie Island meteorological record for August for the period 1970–2008, with monthly total precipitation (top panel), monthly mean wind speed (second panel), monthly mean temperature and dew-point temperature (third panel) and monthly mean surface level pressure (bottom panel).

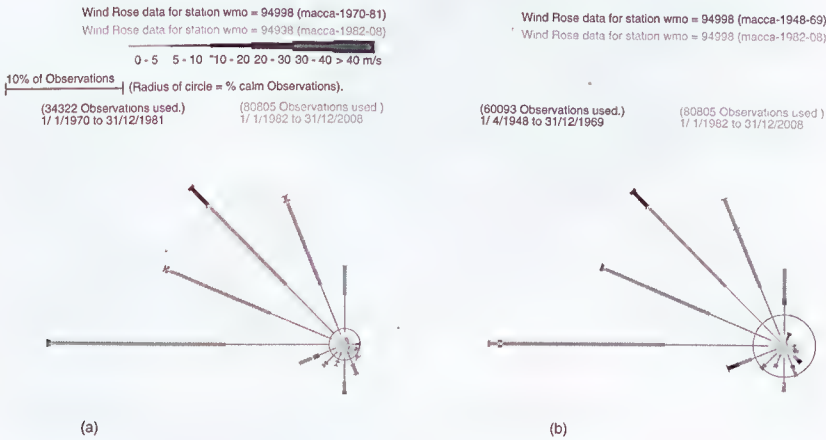
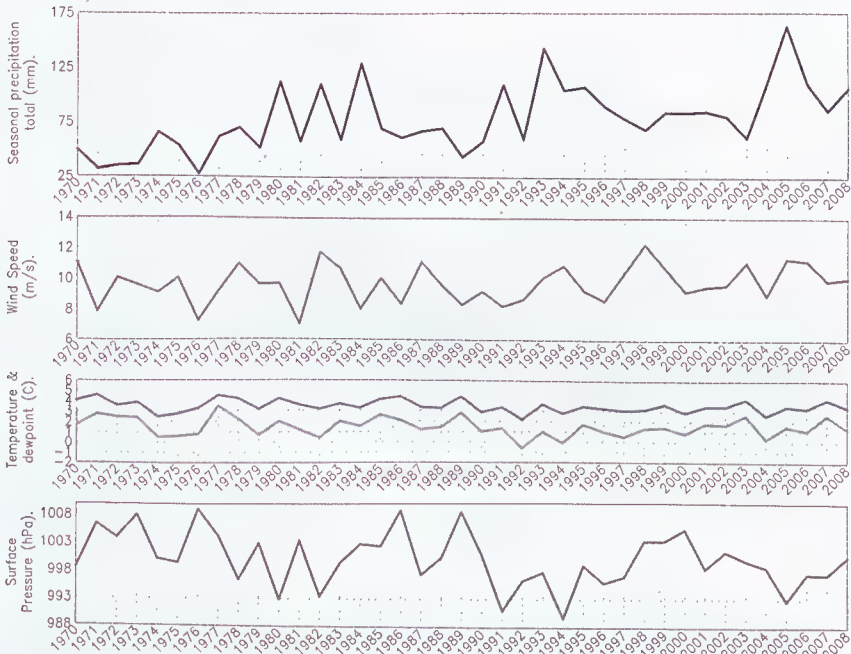


FIG. 5 — Macquarie Island near-surface wind rose comparison for (A) the period 1970–81 and the period 1982–2008; and (B) the period 1948–69 and the period 1982–2008.

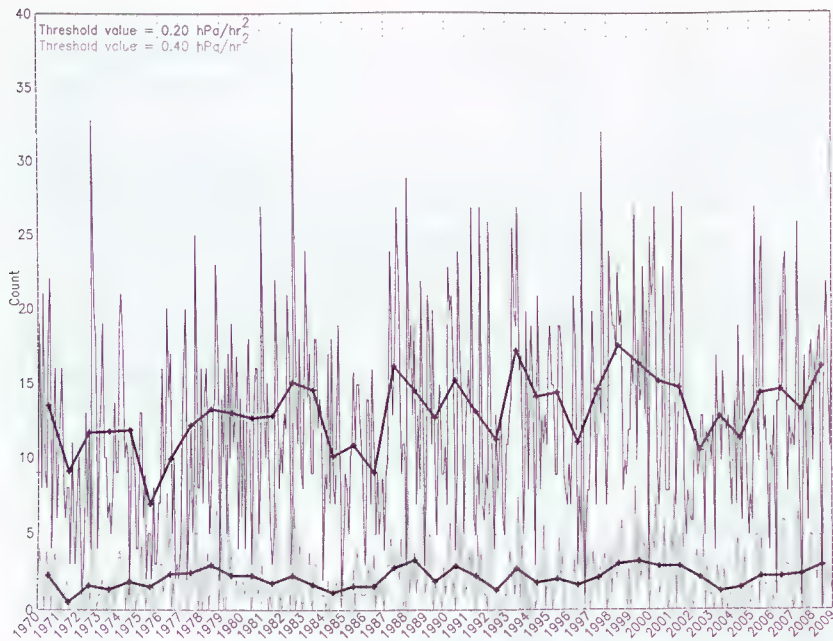


FIG. 6 — Significant pressure change events at Macquarie Island, expressed as the number of events in each month where the second order derivative of surface pressure with respect to time exceeded threshold values of 0.20 and 0.40 hPa/hr². The annual mean monthly count for both threshold values is also plotted as thicker dark lines.

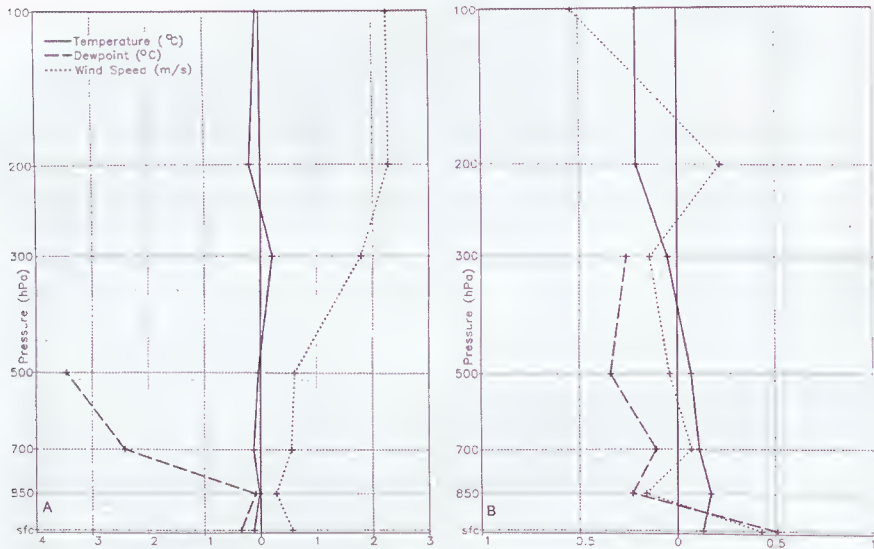


FIG. 7 — Upper air anomalies for temperature, dew-point temperature and wind speed for (A) the period 1982–2008 minus the period 1970 to 1981; and (B) the period 2000–2008 minus the period 1990–99.

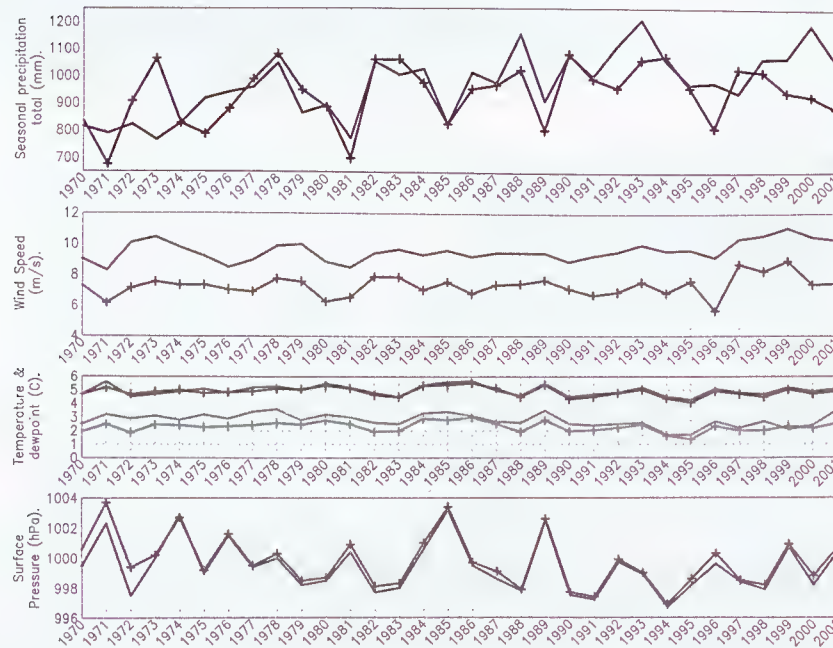


FIG. 8 — A comparison of annual mean data from the Macquarie Island observations record and data from the closest grid point in the ERA40 re-analysis dataset (55°S 160°E, with annual total precipitation (top panel), mean wind speed (second panel), temperature and dew-point temperature (third panel) and surface pressure (bottom panel).

and pressure record is that the number of cyclonic events crossing the island has increased, resulting in an increase in the number of larger precipitation events.

Meteorological changes at Macquarie Island have not been confined to near the surface. An analysis of radiosonde data from 1970–2008 also shows clear changes throughout the troposphere and stratosphere. Figure 7a shows the changes in the mean upper air wind speed, temperature and dew-point fields post-1980. The temperature signal is very weak with a very slight cooling in the lower troposphere below 500 hPa, and slight warming in the upper troposphere. The stratosphere (above 300 hPa) has shown a slight cooling. Wind speeds have increased throughout the atmosphere, but most notably in the stratosphere. The dew-point record only extends to 500 hPa for the earlier part of the period; however, there has been a dramatic drying in the free atmosphere between 850 and 500 hPa (approximately 5000–18 500 feet), which is unlikely to be associated with humidity sensor changes. Figure 7b highlights the changes from the decade pre-2000 to post-2000, where a small temperature increase in the lower troposphere is evident, as is a continued drying in the free atmosphere. Tropospheric wind speeds haven't altered dramatically, apart from a slight increase in near-surface wind speed.

In summary, an analysis of the weather record at Macquarie Island has highlighted a shift in the weather regime around 1982, to a pattern that is slightly windier, and drier through the free atmosphere compared with the pre-1982 climate. The higher precipitation totals are consistent with an increase in significant cyclonic weather events, occurring in a background atmosphere that is drier, with the increases most notable during the winter months. The increased mean wind speed, coupled with the drier atmosphere has probably led to an increase in surface evaporation and a drying of the island surface, although there are no evaporation records from the island to verify this. The increases in wind speed and decreases in free atmosphere dew-points appear to agree with the trends noted by Fyfe (2003). However, the increase in precipitation appears to be at odds with his findings. An analysis of ERA-40 re-analysis data in the following section attempts to address this issue in defining the regional nature of the sub-Antarctic zone.

ERA-40 RE-ANALYSIS DATA OVER THE SUB-ANTARCTIC

The European Centre for Medium Range Weather Forecasting (ECMWF) has undertaken a re-analysis project (ERA40) to produce an analysis dataset of the global atmosphere spanning the period 1957–2002. These analyses are generated using all available surface, upper air and satellite observations, and assimilated within a modern Numerical Weather Prediction model to produce a four-dimensional grid of weather elements spanning the global troposphere and stratosphere, four times a day for the full period (Uppala *et al.* 2005). The ERA40 re-analysis dataset is just one of several datasets available to researchers, with the other most notable being the NCEP-NCAR re-analysis project (Kalnay *et al.* 1996). However, several studies have highlighted issues with the NCEP/NCAR re-analysis data at high southern latitudes (Marshall 2003, Bromwich & Fogt 2004) and noted the improved representation of high southern latitudes within the ERA40 data. Both studies highlighted the significant improvement in the re-analyses post-1979 as a result of the introduction

of satellite data into the analysis system, and Bromwich *et al.* (2004) further noted that the quality of the ERA40 analyses did improve from 1970 onwards.

To highlight the accuracy of the ERA40 re-analyses, monthly means of near-surface weather parameters from the analysis grid-point closest to Macquarie Island were extracted for the period 1970–2002 and compared to the observations from Macquarie Island (fig. 8). Several key points are of note from the comparison. First, the ERA40 precipitation analysis does not increase as much as observed over the 32-year period, although there is an upward trend. Second, the re-analysis wind speeds are lower than observed. However, the remaining variables of temperature, dew-point and surface pressure are remarkably well-structured within the re-analysis data. Observations of precipitation are not assimilated by the re-analysis system but are generated through parameterisation schemes within the numerical weather prediction (NWP) model. These parameterisation schemes may not necessarily capture all of the physical process involved in the hydrological cycle. For example, the resolution of the re-analysis system is such that Macquarie Island is not resolved and the grid point used within the system is entirely oceanic, meaning that no orographic influences on the precipitation would be present. The weaker wind speeds within the model may be a reflection of the relatively coarse horizontal resolution of the model (approximately 125 km), or the parameterisation scheme used to reduce the model wind speeds down to the 10 m level. However, the trends in the wind speed are very well reproduced over the 32-year period.

To further investigate the dynamical reasons behind the shift in Macquarie Island weather post-1981 the long-term differences in the ERA40 near-surface wind and pressure were compared for the period 1970–81, and 1982–2002. Figure 9 shows the difference field of wind speed (greyscale shaded) between the two periods, with the contour analysis showing the surface pressure differences. In broad terms there is a notable increase in the speed of the westerly flow in the sub-Antarctic zone (50°S–60°S) over much of the hemisphere,

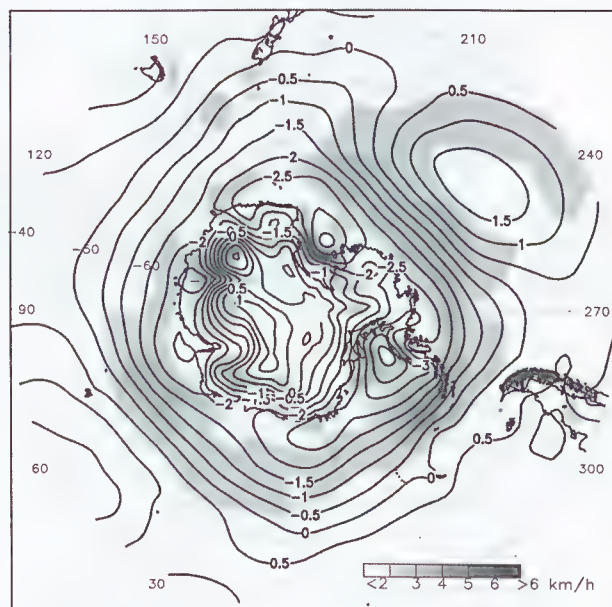


FIG. 9 — ERA40 difference pattern in near-surface wind speed (greyscale shaded plot) and sea level pressure (contour analysis) for the period 1982–2002 minus the period 1970–81, over the mid- to high latitudes of the Southern Hemisphere.

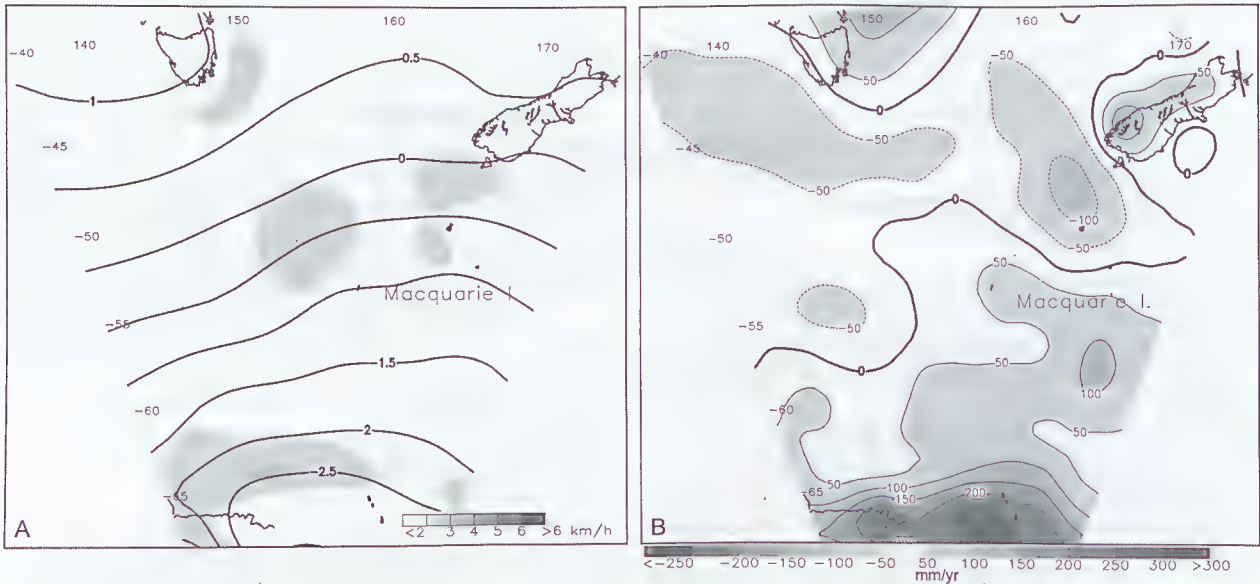


FIG. 10 — ERA40 difference patterns over the Macquarie Island sector for (A) near surface wind speed (greyscale shaded plot) and sea level pressure (contour analysis) for the period 1982–2002 minus the period 1970–81; and (B) precipitation for the period 1982–2002 minus the period 1970–81.

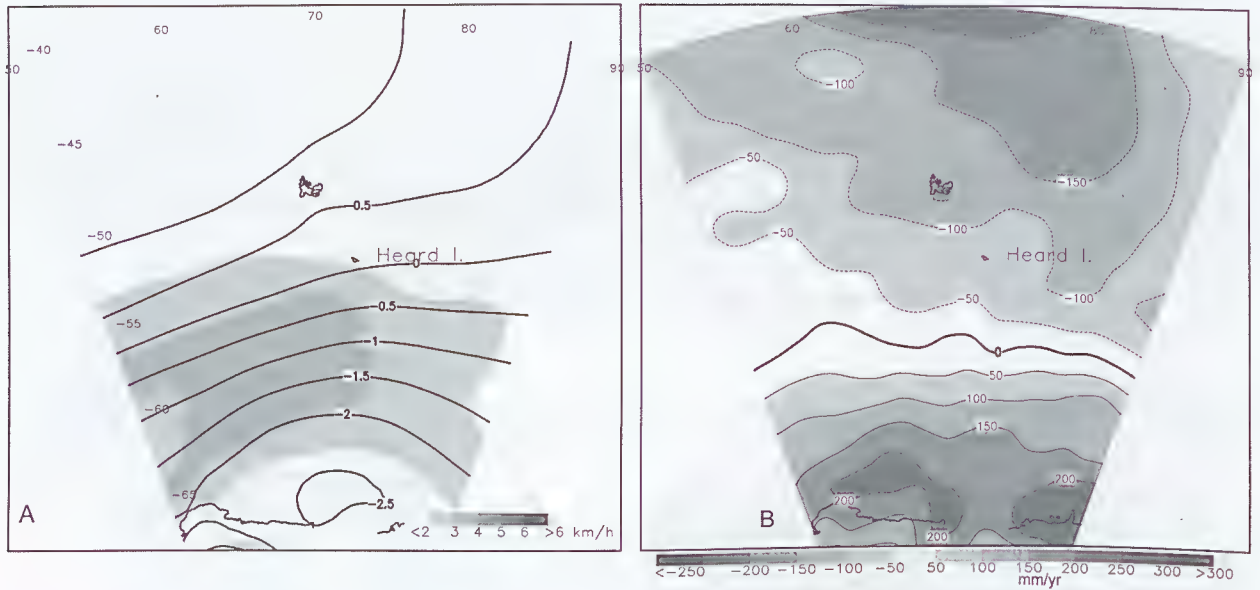


FIG. 11 — ERA40 difference patterns over the Heard Island sector for (A) near surface wind speed (greyscale shaded plot) and sea level pressure (contour analysis) for the period 1982–2002 minus the period 1970–81; and (B) Precipitation for the period 1982–2002 minus the period 1970–81.

although less so immediately to the south of Australia. The increasing westerly flow is consistent with the studies (e.g., Fyfe 2003) showing an increase in the Southern Annular Mode (SAM) index (Marshall 2003) over the past several decades. In the longitudes of Macquarie Island the most notable feature in figure 9 is the strong trough of low pressure in the westerly flow extending out of the Antarctic trough near Cape Adare (170°E) and northward just east of New Zealand. Figure 10a highlights the Macquarie Island area of figure 9 and the shift to more cyclonic flow over the island is quite evident. The difference field in precipitation is shown in figure 10b and the associated increase in precipitation associated with the increase in cyclonic activity is evident over the island and to the southeast and south.

The regional differences in changes over the past two decades shown in figure 9 are quite marked, and the need to be careful in making generalised statements about changes across the entire sub-Antarctic obvious. Figure 11 shows the same information as in figure 10 but for the area around Heard Island, and quite clearly the changes at Heard Island are significantly different to those at Macquarie Island. Wind speeds have increased slightly and the flow may even have become slightly more cyclonic as at Macquarie Island. However, Heard Island has experienced slight increases in pressure and the annual precipitation totals have fallen quite significantly in the ERA40 re-analyses, consistent with the generalised statements of changes in the sub-Antarctic by Fyfe (2003), and comparable analyses using the NCEP-NCAR reanalysis data (<http://www.bom.gov.au/cgi-bin/climate/change/trendmaps.cgi>).

FUTURE TRENDS IN THE SUB-ANTARCTIC

Little may be found in the literature specifically addressing the issues of climate variability and change in the sub-Antarctic. From an analysis of transient climate change scenarios spanning 1850–2100 based on the Global Climate Model (GCM) from the Canadian Centre for Climate Modelling and Analysis (CCCma), Fyfe (2003) concluded that under a “business as usual” carbon emissions scenario, the number of sub-Antarctic Ocean (40°S–60°S) cyclones would continue to fall and be at 30% of early twentieth-century numbers by the end of the century, with the depth of these cyclones also diminishing. The analysis also concluded that the number of Antarctic Ocean cyclones would increase which is consistent with a poleward shift in the baroclinic zone and increasing westerly flow through the southern regions of the sub-Antarctic. The analysis looked at sub-Antarctic-wide statistics but, as previously mentioned, the ERA40 re-analysis data show quite strong regional differences across the sub-Antarctic.

In the IPCC AR4 a multi-model approach was taken to assess likely atmospheric changes out to the end of the twenty-first century. In an analysis of the mid- to high carbon emissions scenario (A1B) AR4 (chapter 10, IPCC 2007) also concluded that the observed increasing trend in the SAM index would continue out to the end of the century. However, the report differed in the expected changes in precipitation across the sub-Antarctic, highlighting significant regional and seasonal differences. Figure 10.9 from the report (see link to chapter 10 under <http://www.ipcc.ch/ipccreports/ar4-wg1.htm>) highlights the expected changes between the multi-model means for the period 2080–99 relative

to 1980–99. During the sub-Antarctic summer months a statistically significant reduction in precipitation is expected from the sub-tropics southward to around 50°S, although with a distinct three-wave pattern with areas of increased precipitation along the east coast of South America, south of Madagascar and in the longitudes of Macquarie Island and New Zealand, although not at a statistically significant level. Statistically significant summer-time increases in precipitation are expected between 55°S and 65°S. During the winter months the multi-model ensemble mean shows a statistically significant increase in precipitation over much of the sub-Antarctic and, notably, highlights local maxima in the increase in the Macquarie Island longitudes. The winter-time pressure trends in figure 10.9 from the report highlight a deepening of the polar trough immediately to the south of Macquarie Island, with an increase in surface pressure over Australia and the north island of New Zealand, giving a trend towards a strengthening winter-time long wave trough just west of Macquarie Island.

CONCLUSIONS

An analysis of the Macquarie Island observational record has shown a clear trend in increasing precipitation and a modest increase in wind speed on the island over the past four decades, consistent with the expected response to a globally changing climate under increased greenhouse gases. Re-analysis data from the ERA40 project has captured the changing sub-Antarctic environment, characterised by increasing westerly flow in the mid-latitudes with a corresponding drying, increased cyclonic activity to the south of the sub-Antarctic resulting in regional increases in precipitation over parts of the sub-Antarctic, particularly during winter. Analysis of the multi-model output for the A1B scenario from the IPCC AR4 climate projections suggests a continuation of these trends over the twenty-first century although the details of these changes over the sub-Antarctic are not well resolved.

The sub-Antarctic needs a more careful analysis of the past and current climate to better understand the atmospheric dynamics and the likely responses of the system over the coming decades to climate change forcing.

ACKNOWLEDGEMENTS

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EXPLOITATION OF THE MARINE ECOSYSTEM IN THE SUB-ANTARCTIC: HISTORICAL IMPACTS AND CURRENT CONSEQUENCES

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(with one text-figure)

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The Southern Ocean is often portrayed as the last great wilderness. However, the marine living resources of the sub-Antarctic islands have been harvested for over two centuries. Exploitation began with the upper trophic levels and the high-value air-breathing species, before progressing down the food chain to the lower trophic levels and the less valuable nekton and zooplankton. Exploitation in the sub-Antarctic began in the late eighteenth century, nowhere better typified than at South Georgia. At South Georgia exploitation started with Antarctic Fur Seals, *Arctocephalus gazella*, which were reduced almost to extinction by the mid-nineteenth century. As the fur trade rapidly became uneconomic, new targets were sought and by the end of the nineteenth century, oilers were hunting for Southern Elephant Seals, *Mirounga leonina*, Southern Right Whales, *Eubalaena australis*, and some sub-Antarctic penguin species. As these stocks also declined and their commercial exploitation became uneconomic, the focus shifted such that by the beginning of the twentieth century, harvesting for other baleen whales (the so-called rorquals) and Sperm Whales, *Physeter macrocephalus*, was well-established. With the demise of the great whales, other less valuable species were then sought, so that by the latter half of the twentieth century, fishing for finfish and krill had begun. Removal of the upper trophic level species has impacted upon the sub-Antarctic marine system resulting in profound changes, the consequences of which continue to the present. The consequences of such harvesting are reviewed in the context of an ecosystem model that demonstrates some of the expected changes in the marine foodweb that may arise as a consequence of harvesting and how, once harvesting ceases, populations may recover to their pre-exploitation state. The current status of the South Georgia foodweb is reviewed in the context of these predicted changes. In the period since uncontrolled harvesting ceased, the role of physical environmental forcing factors has been recognised and found to be key to any understanding of marine foodweb dynamics. These two major forces, historical exploitation and climate change, may act in concert to alter ecosystem dynamics. Disentangling these confounding drivers may be difficult and complex, but because of the relatively well-documented history of exploitation the sub-Antarctic may offer one location where it is feasible.

Key Words: Exploitation, marine living resources, sub-Antarctic, ecosystem effects, climate change.

THE HISTORY OF EXPLOITATION IN THE SOUTHERN OCEAN

Despite the remoteness, inhospitability and size of the Southern Ocean, the living resources of its marine ecosystems have been harvested for over two centuries. Though its remoteness from human habitation and commercial markets meant that harvesting did not begin until the late eighteenth century, the subsequent pattern of exploitation followed that of many other parts of the World Ocean. Harvesting started with the large, high-value species in the upper trophic levels, before progressing down the food chain to the smaller, less valuable species at the lower trophic levels (Pauly *et al.* 1998, Jackson *et al.* 2001).

The history of exploitation in the sub-Antarctic is exemplified by South Georgia, the crucible of exploitation for seals and the great whales in the southern hemisphere, and arguably for the world. The first recorded landing was on 17 January 1775 by the then Commander, later Captain, James Cook. The exploitation of the wildlife at South Georgia began shortly after Cook returned to Britain and reported the large numbers of fur seals found there. Sealers were initially very successful and the high rate of harvesting of Antarctic Fur Seals, *Arctocephalus gazella* (Peters, 1875), meant that the fur trade rapidly became uneconomic and new targets were sought. By the end of the nineteenth century, Southern Elephant Seals, *Mirounga leonina* (Linnaeus, 1758), Southern Right Whales, *Eubalaena australis* (Desmoulins, 1822), and some sub-Antarctic penguins were being harvested for oil.

As these stocks also declined and became uneconomic, the focus shifted once again, such that by the beginning of the twentieth century, harvesting for other baleen whales and Sperm Whales, *Physeter macrocephalus* Linnaeus, 1758, was well established. With the demise of the great whales, other less valuable species were then sought, so that by the latter half of the twentieth century, fishing for finfish and Antarctic Krill, *Euphausia superba* Dana, 1852, had begun.

Much of the history of the exploitation of the Southern Ocean is well documented in previous work (Laws 1953, Bonner 1980, 1984, Everson 1977, Headland 1992, Kock 1992). The following review has drawn heavily on their source material.

The main targets for exploitation both at South Georgia and more generally in the Southern Ocean are discussed below.

Antarctic and sub-Antarctic Fur Seals

Hunting for seals began on the sub-Antarctic islands in about 1778, when Antarctic and sub-Antarctic, *Arctocephalus tropicalis* (J.E. Gray, 1872), Fur Seals were targeted for their skins (Roberts 1958, Bonner 1984). Hunting involved the taking of all demographic classes, with sealing reaching a peak in the 1800–01 season, when the 17 vessels operating at South Georgia took more than 112 000 seal skins in that season (Headland 1992). By 1822, Weddell (1825) estimated that 1 200 000 skins had been taken from South Georgia and the Antarctic Fur Seal was almost extinct on the island. This same pattern of unregulated exploitation occurred at

many of the other sub-Antarctic island archipelagos, such as at Tierra del Fuego, Gough Island, Tristan da Cunha, Bouvetøya, the Prince Edward Islands, Îles de Crozet, Île de Kerguelen, McDonald Island and at Macquarie Island, albeit with different timings. Exploitation also moved further south, for example fur seals at the South Shetland Islands were first exploited in 1819–20, but the smaller stocks there and at the South Orkney Islands and the South Sandwich Islands meant these were also rapidly depleted.

Most populations of Antarctic and sub-Antarctic Fur Seals were on the verge of extinction by 1825. In subsequent years, sealing was intermittently resumed when fur seal populations showed some signs of recovery, indeed it continued until the early days of the twentieth century (Headland 1992). The last sealing expedition was to South Georgia in 1907, when 170 skins were taken (Larsen 1920).

Southern Elephant Seal

The rendering and extraction of oil from Southern Elephant Seals began towards the end of the eighteenth century when the exploitation of fur seals declined, though both species were often exploited at the same time and in parallel (Headland 1992). Oil from Southern Elephant Seals was less valuable than the skins from fur seals, it was also more labour intensive to collect; therefore Southern Elephant Seals were not pursued to the same extent as fur seals and populations were not taken to such low numbers (Bonner 1984). The large breeding colonies at South Georgia, the Île de Kerguelen, Heard Island, McDonald Island and Macquarie Island were the main centres for the sealers. Unregulated sealing stopped at most places within the first two decades of the twentieth century (Headland 1992). A controlled harvest of male Southern Elephant Seals was continued at South Georgia from 1909–1964 and at Île de Kerguelen from 1958–1961 (Bonner 1984). The harvest at South Georgia has been highlighted in the past as a good example of the rational management of a natural living resource (Laws 1953, Bonner 1958, 1984).

Seabirds

King Penguins, *Aptenodytes patagonicus* J.F. Miller, 1778, and crested penguins (*Eudyptes* spp.) were exploited for oil, food and as fuel for fire on some of the sub-Antarctic islands, such as at South Georgia, Heard Island and Macquarie Island, during the sealing period of the eighteenth and nineteenth centuries. Subsequently, the numbers of King Penguins have increased rapidly at all breeding sites – in the range of 8–12% per annum on most sub-Antarctic islands since the 1960s. The largest populations are at the Îles de Crozet (700 000 pairs), South Georgia (450 000 pairs) and Macquarie Island (110 000 pairs).

Eggs of a number of other species, including Chinstrap Penguins, *Pygoscelis antarctica* (J.R. Forster, 1781), and Adélie Penguins, *P. adeliae* (Hombron & Jacquinot, 1841), in the Antarctic and of Wandering Albatross, *Diomedea exulans* Linnaeus, 1758, and Black-browed Albatross, *Thalassarche melanophrys* (Temminck, 1828), in the sub-Antarctic were harvested by sealers and whalers well into the 1950s, when the taking of eggs ended (Bonner 1984). The effects this eggging may have had on bird populations are unknown (Bonner 1984).

Whales

Commercial whaling in the Antarctic began in December 1904 at Grytviken on South Georgia. It then expanded to other

locations on South Georgia and then to the more southerly islands of the Scotia Arc and to Île de Kerguelen (Bonner 1980). Until the early 1920s, whaling was essentially land-based, with catchers towing dead whales to the processing plants either at shore stations or on factory vessels moored in sheltered fjords and bays (Headland 1992). Whaling became pelagic from 1925 onwards, when factory vessels began to be fitted with stern slipways; after this, pelagic operations based around mother ships and associated catcher vessels, became the most common type of whaling.

Seven species (including subspecies) of baleen whales (Mysticeti) occur in the Southern Ocean, south of the Antarctic Polar Front, and all have been extensively exploited in the past. Of the toothed whales (Odontoceti), only Sperm Whales were taken regularly and in appreciable numbers. Killer Whales, *Orcinus orca* Linnaeus, 1758, and Southern Bottlenose Whales, *Hyperoodon planifrons* Flower, 1882, were also taken occasionally, but then only in small numbers.

Production at South Georgia, in terms of barrels of oil, peaked in the 1926–27 season, and in terms of whale numbers, the previous season (Headland 1992). More generally, across the Southern Ocean, whale catches peaked in the 1930s when pelagic operations prevailed (Bonner 1980). From this time onwards species successively became commercially unviable, and consequently smaller, less valuable species were targeted and began to form a larger proportion of the catch (Bonner 1980). The smallest species, Minke Whales, *Balaenoptera acutorostrata* Lacépède, 1804, were not exploited in appreciable numbers until the early 1970s, but they then became the main target until 1987 when major whaling operations ceased (Bonner 1980). Thus, Bonner (1984) shows that first Blue Whale, *B. musculus* (Linnaeus, 1758), then Fin Whale, *B. physalus* (Linnaeus, 1758), and eventually Sei Whale, *B. borealis* Lesson, 1828, numbers were reduced, until finally Minke Whales were targeted until the cessation of large-scale harvesting.

The total catch of whales reported from the Antarctic between 1904 and 1987 was more than 1.15 million animals or approximately 65 million tonnes (based on catch statistics held by the International Whaling Commission and assuming average weights for each species), though catch records have been revised by the IWC and will probably continue to form an area of contested discussion. A portion of this catch, in particular of Sperm Whales, Pygmy Blue Whales, *B. musculus brevicauda* Ichihara, 1966, and Sei Whales, was taken north of the Antarctic Polar Front in the 1960s and 1970s. However, it seems reasonable to assume that, prior to Antarctic whaling, nearly a million whales may have moved through the sub-Antarctic in the austral summer and autumn every year (Laws 1977). With the exception of Minke Whales, and probably Killer and Southern Bottlenose whales, the numbers of all species declined dramatically during the harvest and are currently only small fractions of their pre-exploited population sizes.

Finfish

Plans to develop fisheries for finfish in the Southern Ocean date back to the early days of land-based whaling at South Georgia in 1906 (Headland 1992), although large-scale harvesting of finfish did not begin until the late 1960s at South Georgia and the early 1970s around Île de Kerguelen (Everson 1977). After 1978, the finfish fisheries expanded to the South Orkney Islands and to more southerly grounds. These southern grounds yielded good catches for only a few

years and declined rapidly by the early 1980s. Until the mid-1980s the finfish fisheries were entirely trawl fisheries.

The species that have been targeted by the trawl fisheries include Marbled Rockcod, *Notothenia rossii* Richardson, 1844; Mackerel Icefish, *Champsocephalus gunnari* Lönnberg, 1905; Grey Rockcod, *Lepidonotothen squamifrons* (Günther, 1880); Yellowfin Notothen, *Patagonotothen guntheri* (Norman, 1937); Sub-Antarctic Lanternfish, most plausibly *Electrona carlsbergi* (Tanning, 1932); and Wilson's Icefish, *Chaenodraco wilsoni* Regan, 1914, (Kock 1992). Frequent by-catch species have included various icefish species, Humped Rockcod, *Gobionotothen gibberifrons* (Lönnberg, 1905) and skates, (*Amblyraja georgiana* (Norman, 1938) and *Bathyraja* spp.) (Kock 1992). Most species have been harvested for human food, while the lanternfish, and in some cases, the retained by-catch species, were mainly used for fishmeal (Kock 1992).

Catches for some targeted species were initially high, but declined very rapidly thereafter. For example, Marbled Rockcod catches at South Georgia were initially very high, with approximately 400 000 tonnes in the first season in 1969–1970 and approximately 100 000 tonnes the following season. The stock was so depleted by this initial take, that biomass has remained low ever since and has not recovered some 40 years later (Kock 1992). The same patterns were seen elsewhere in the Antarctic, principally at the South Orkney Islands, the Antarctic Peninsula and Île de Kerguelen (Kock 1992).

In the mid-1980s demersal longlines were introduced to catch Patagonian Toothfish, *Dissostichus eleginoides* Smitt, 1898, primarily around South Georgia and at the Île de Kerguelen as well around other sub-Antarctic islands (Agnew 2004).

Antarctic Krill

Fishing for Antarctic Krill began on a commercial scale in 1972 (www.fao.org; accessed 26 June 2009), starting at South Georgia in 1975–76 (Agnew 2004). It rapidly focused on three main fishing grounds: to the east of South Georgia, around the South Orkney Islands and to the north of the South Shetland Islands. Catches peaked in 1981–82, when 528 201 tonnes were landed, 93% of which was taken by the Soviet Union. In the following years catches stabilised at

approximately 300 000–400 000 tonnes, or about 13% of the world catch of crustaceans at that time (www.fao.org). When economic factors forced the Soviet fleet to stop fishing, catches declined dramatically after 1991–92 to about 100 000 tonnes per annum.

ECOSYSTEM CONSEQUENCES OF EXPLOITATION OF THE SUB-ANTARCTIC

The ecosystem consequences of such a large and rapid removal of upper-trophic level species have been the subject of a great deal of scientific debate, conjecture and disagreement (see for example Ainley *et al.* 2007 and Nicol *et al.* 2007 and references therein). Of course the difficulty in determining and quantifying what effects might have been propagated through the Antarctic and sub-Antarctic ecosystem is that there is no information upon which to assess the pre-exploitation status of the marine system. While it is possible to make some qualitative inferences that fur seals were very numerous, prompting Cook to return home with the descriptions that enticed sealers to venture to these new areas, quantitative assessment is not now possible. Nevertheless, it is feasible to examine potential scenarios using mathematical models that provide a representation of the operation of the Antarctic and sub-Antarctic marine ecosystem (see Hill *et al.* 2006 for review). In this paper, rather than consider the merits of different models, we use the model of Murphy (1995) as an illustration of the potential changes in linked predator and prey species that might have arisen from historical exploitation and the subsequent trajectories that populations follow upon the cessation of harvesting. This model is based upon the “krill-centric” ecosystem of the South Georgia region and describes the population trajectories of seals, penguins, whales and krill from the period prior to the discovery of South Georgia to beyond the present day (fig. 1).

In the context of the Murphy (1995) model (hereafter simply referred to as “the model”) the present day is approximately the year 2000. Here we compare contemporary data on the trends in the population size of the key ecosystem components (seals, penguins, whales and krill), with their population trajectories described by the model.

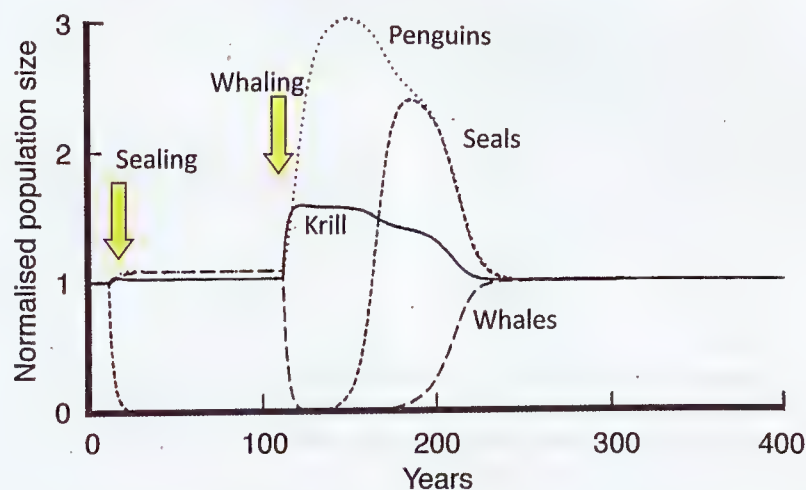


FIG. 1 — Output of a simulation model to examine the impacts of harvesting (sealing and whaling), on other ecosystem components; modified from Murphy (1995) with permission of the author.

Fur seals

The model indicates that population of fur seals would currently be in a period where the growth rate has slowed, or even stopped, following a period of rapid increase. Recent data on the population size of fur seals is lacking. However, the most recent survey of the South Georgia population, carried out in 1991 (Boyd 1993), indicated that the population growth rate had decreased from the exceptionally high 16.8% in the period 1955–71 (Payne 1977) to 9.8% in the period 1977–90. Data from long-term monitoring at a seal study areas on Bird Island (see Forcada *et al.* 2005) indicate that the number of pups born annually on that beach has also actually decreased over the period 1984–85 to 2003–04.

Penguins

The model indicates that penguin populations would now be in decline, following a rapid increase associated with the removal of potentially competing species that consumed the same prey. The major krill-consuming penguin species at South Georgia is the Macaroni Penguin, *Eudyptes chrysolophus* (Brandt, 1837), (Croxall & Prince 1980) and data from Bird Island indicate that the population there has fallen by almost 50% over the past two decades between 1980 and 2000 (Trathan *et al.* 1998, Trathan 2004).

Whales

The increase in the number of whales indicated by the model is difficult to compare with any contemporary data because of the paucity of whale population survey data from the South Georgia region (or indeed from any other part of the sub-Antarctic). However, it is possible to infer the likely changes in numbers of whales in the region based on knowledge of the changes in breeding population size, from counts in the calving areas, of whale stocks that forage in the South Georgia region. Two such stocks, both of which feed around South Georgia during the summer months and both of which are increasing, are the Humpback Whales and Southern Right Whales that calve in the coastal waters off Brazil and Argentina respectively (Zerbini *et al.* 2004; Leaper *et al.* 2006).

Krill

The model clearly indicates that there is an expectation of a declining krill population and data from a variety of net samples collected over the period 1976–2003 indicate that there has actually been a decline in krill in the southwest Atlantic region, possibly of >50% (Atkinson *et al.* 2004, 2008).

From the summary above it is now apparent that there are indications of change in the populations of the taxa represented in the model and that these are broadly consistent with the predictions of the model. There is, of course, a number of caveats, as with any model that attempts to represent a subset of the real world. We do not raise these as a criticism of the model, simply as a reflection of the difficulty in parameterising both the individual components and the covariation between them given the uncertainties in those factors.

Such uncertainties can arise from inadequacies in the available data, for example the model ‘assumes’ that there was a cessation in the commercial exploitation of the great whales following the moratorium introduced in 1987. However, it is now clear that illegal whaling occurred in areas of the Southern Ocean subsequent to the introduction of that moratorium (see for example, Clapham & Yushenko 2009). This has the potential to delay the recovery of whale

populations as well as to influence other components of the model that are linked to the consumption of krill by those whales.

Uncertainties also arise from some (possibly) small-scale interactions that were not included in the model. Thus, in the model, penguin population processes might be perceived as responding to changes in prey abundance introduced into the model by population of other species, particularly marine mammals. However, as described above, populations of some penguin species were also heavily exploited and their population processes might equally be responding to this historical harvest. Thus, though it is important to recognise that the harvesting of penguins is unlikely to have had the same scale of ecosystem consequences as those that involved marine mammals (given their lower biomass prior to commercial exploitation), it is likely to have had at least some impact upon some population trajectories over the same time-scales.

Uncertainties also arise from effects not perceived as important at the time the model was developed, but which have subsequently been shown to be of major importance. Thus, one of the critical assumptions of the model described here is that it seeks to describe causes and effects. Thus, when an ecological force (in this case the exploitation of seals and whales) is applied, the ecosystem responds, and when the force is removed (that is, sealing and whaling cease) the system returns to its initial pre-exploitation state following some time period that accounts for ecosystem lags and interactions. However, it is now apparent from long-term studies of populations of seals, penguins and whales (Forcada *et al.* 2005, Trathan *et al.* 2006, Leaper *et al.* 2006), that climate variability can impact the reproductive output and population trajectory of these species, mediated through their prey, Antarctic Krill (Murphy *et al.* 2007). Indeed, Whitehouse *et al.* (2008) have recently shown that over the period 1925–2006, there have been long-term changes in ocean temperatures at South Georgia at a scale that would be expected to impact upon Antarctic Krill and hence the reproductive performance of seals, penguins and whales. However, it is not currently possible to estimate the species-specific consequence of such changes, given the differences in the magnitude and the time lag of response for each taxonomic group. Nevertheless, it is important to recognise that the interacting forces of historical exploitation and changes in ecosystem operation brought about by changes in regional climate will have a strong influence on the population trajectories of species and their return to any pre-exploitation state.

This confounding interaction between the consequences of historical exploitation and changing climate makes the interpretation of present-day signals of climate change problematic (Croxall *et al.* 2002). For example, in describing the decline in krill, Atkinson *et al.* (2004) provided a plausible link between the decline in the spatial extent and duration of sea-ice and declining krill populations over the same time-period (since sea-ice provides a critical habitat for the early life-history stages of krill). However, such a decline in krill should be anticipated anyway, simply as a consequence of the population processes associated with the historical exploitation of krill predators. In this case the two drivers of change, historical exploitation and recent sea-ice reduction, would have a complementary effect on the population of krill such that climate-related changes could accelerate a decrease that was already occurring as a legacy of historical exploitation.

Such confounding interactions are not unique to the sub-Antarctic; the World Ocean has been highly perturbed by exploitation (see Myers & Worm 2003, 2005) and is now responding in different ways to changes in climate. However, one aspect that potentially makes the sub-Antarctic different to other parts of the World Ocean is the rates of these changes. While humans had been removing large, air-breathing species such as whales and seals from more accessible regions of the Atlantic and Pacific for several centuries, the changes in the Southern Ocean have only occurred over a 200-year time span. During this relatively recent time period, the level of exploitation has been unusually well-documented; at least in comparison with other areas of the World Ocean. Similarly, while there has been a great deal of variability in the response of the World Ocean to climate change, it is the southwest Atlantic sector, including the Antarctic Peninsula, that is warming more rapidly than almost any region on the planet (Vaughan *et al.* 2003, Turner & Overland 2009). Therefore, while it may be easy to point to the interacting forces and the consequent difficulties of distinguishing the combined drivers of change, it may be that the sub-Antarctic actually provides a unique region within which to consider the interacting historical and contemporary drivers of change.

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DYNAMICS OF PHYSICAL AND BIOLOGICAL SYSTEMS OF THE PRINCE EDWARD ISLANDS IN A CHANGING CLIMATE

by I. J. Ansorge, J. V. Durgadoo and E. A. Pakhomov

(with four text-figures)

Ansorge, I.J., Durgadoo, J.V. & Pakhomov, E.A. 2009 (11:xii): Dynamics of physical and biological systems of the Prince Edward Islands in a changing climate. *Papers and Proceedings of the Royal Society of Tasmania* 143(2): 15–18. ISSN 0080-4703. Oceanography Department, Marine Research Institute, University of Cape Town, Rondebosch 7701, South Africa (IJA*, JVD), Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, V6T 1Z4, Canada (EAP). *Author for correspondence. Email: Isabelle.ansorge@uct.ac.za

Sub-Antarctic islands are classified as isolated, hostile, impoverished regions, in which the terrestrial and marine ecosystems are relatively simple and extremely sensitive to perturbations. They provide an ideal ecological laboratory for studying how organisms, ecological processes and ecosystems respond to a changing ocean climate in the Southern Ocean. These islands are characterised by large populations of top predators and subsequently any changes in the oceanographic frontal dynamics associated with the Antarctic Circumpolar Current, either in the vicinity of these islands or further afield, may have strong implications on their foraging behaviour. The relatively easy accessibility of the Prince Edward Islands from South Africa and their location between the main frontal systems bordering the Antarctic Circumpolar Current enable high-resolution synoptic field studies to be undertaken. Such studies have provided information on the impact changes in the large-scale ocean dynamics have on the local marine ecosystems.

Key Words: Prince Edward Islands, ocean variability, Sub-Antarctic Front.

INTRODUCTION

The oceanic thermohaline circulation, often referred to as the ocean's "conveyor belt", is a vital link in the global transport of heat from the tropics to higher latitudes. The physical structure of this circulation belt and its efficiency in regulating climate is substantially influenced by the nature of water mass exchange between ocean basins (Gordon 1986, Speich *et al.* 2001). The Southern Ocean is the name given to the oceanic region that surrounds the entire Antarctic continent. It comprises the southern extents of the Atlantic, Indian and Pacific oceans, with the Antarctic continent forming the southern boundary of the Southern Ocean, while the northern border is not physiographically fixed, but is usually considered to coincide with the geographic location of the Subtropical Convergence (Lutjeharms 1985). Dominating the flow of the Southern Ocean is the Antarctic Circumpolar Current (ACC), which, extending unbroken around Antarctica, is the primary means by which heat and salt are transferred between different ocean basins. The major part of the flow associated with this current is concentrated at a number of circumpolar fronts (fig. 1), which act as boundaries separating zones of uniform water masses. Although these fronts are circumpolar they show a strong temporal variability in latitude between different oceanic sectors (Lutjeharms 1985).

Recent studies have shown that since the 1950s the ACC has strengthened and migrated southwards by 50–70 km, resulting in an increase in global ocean temperatures in the upper 1000 m (Gille 2002). The most rapid warming appears to be concentrated along the Sub-Antarctic Front (SAF) and may be linked to the formation of Sub-Antarctic Mode Water (SAMW). SAMW is ventilated annually and therefore responds to rapidly changing atmospheric and oceanic conditions (McCartney 1982). Changes of these mid-depth temperatures may imply a net warming and consequently a reduction in the volume of cold circumpolar waters separating the ACC from the Antarctic continent.

Furthermore, recent ocean models have indicated that a southern shift and intensification in the prevailing westerly wind field driving the ACC may result in an increase in the upwelling of deep water masses (Oke & England 2004). Such changes could potentially influence the volume and stability of the cryosphere and may have important consequences on the uptake of anthropogenic CO₂ and hence "the ability of the world ocean to mitigate the impact of global warming" (Fyfe & Saenko 2006 p. 5).

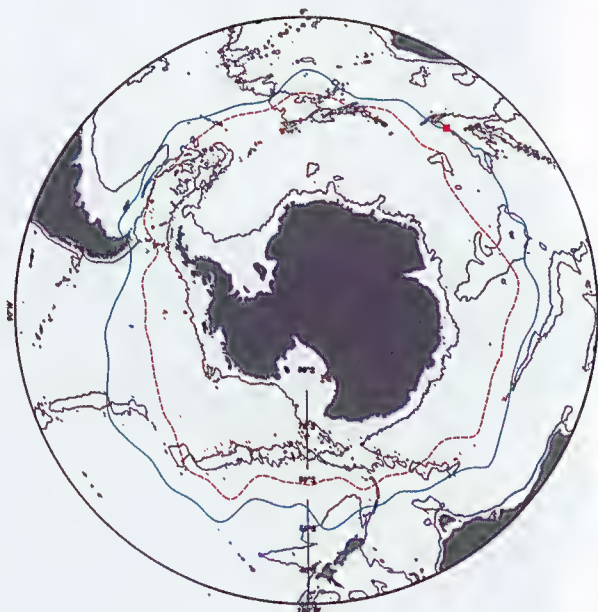


FIG. 1 — Map highlighting the mean position of the subsurface expression of the Sub-Antarctic Front (6°C at 200 m) and Antarctic Polar Front (2°C at 200 m). The location of the Prince Edward Islands can be seen by the red square at approximately 47°S, 38°E.

Straddled between the northern and southern boundaries of the ACC, sub-Antarctic islands are typically oceanic; experiencing moist, cool and windy climates. They are classified as regions in which the terrestrial and marine ecosystems are relatively simple and extremely sensitive to perturbations. This paper focuses on the Prince Edward Islands as a case study to highlight the influence changes in climate conditions have on the marine ecosystem. Lying directly within the ACC, these islands provide an ideal ecological laboratory for studying how shifts in atmospheric and oceanic circulation patterns in the Indian sector of the Southern Ocean will increase the ease with which these islands and their ocean surrounds can be invaded by alien species (Smith 2002).

THE PRINCE EDWARD ISLANDS

The Prince Edward Islands are located in the Indian sector of the Southern Ocean at approximately 46°50"S and 37°50"E. The nearest landfall is the Crozet Island Group 950 km to the east, while South Africa lies over 2000 km to the northwest. Extensive oceanographic surveys have shown that the Prince Edward Islands are sandwiched between the SAF to the north and the Antarctic Polar Front (APF) to the south (Ansorge & Lutjeharms 2002). These fronts separate warm Sub-Antarctic Surface Water (SASW) from cooler Antarctic Surface Water (AASW), with a zone of transition known as the Antarctic Polar Frontal Zone (APFZ) between the two. The SAF and APF demonstrate a high degree of latitudinal variability in this region (fig. 2) and it is thought that the complexity of the ACC in the vicinity of these islands (Ansorge & Lutjeharms

2003) results in an increase in the interchange of Antarctic and sub-Antarctic surface and intermediate water masses (Deacon 1982). Indeed, recent investigations (Ansorge & Lutjeharms 2003, Bernard *et al.* 2007) have identified the region upstream of the Prince Edward Islands as an “eddy corridor” in which eddies formed by the ACC interaction with the shallow southwest Indian Ridge transport physical and biological properties typical of the Antarctic northwards into the island vicinity.

CLIMATE IMPLICATIONS –
A THROUGH-FLOW SYSTEM?

The Prince Edward Islands are seasonally characterised by dense populations of top predators (Hänel & Chown 1998) and subsequently any changes in the frontal dynamics, either in the vicinity of these islands or further afield, may have strong implications on their foraging behaviour. Changes in the intensity and geographic position within these frontal systems are likely to coincide with dramatic changes in the distribution of species and total productivity within the Southern Ocean. It is expected that latitudinal shifts in the positions of oceanic fronts may be coupled to atmospheric changes and will become more dramatic and frequent in response to global climate change.

There is growing evidence that the geographical position of the SAF in the proximity of the Prince Edward Islands plays an important role in forming local macro- and mesoscale oceanographic conditions (Pakhomov *et al.* 2000a, Ansorge & Lutjeharms 2002). Previous investigations have shown that when the SAF lies far north of the islands, the interaction between the ACC and the island group results

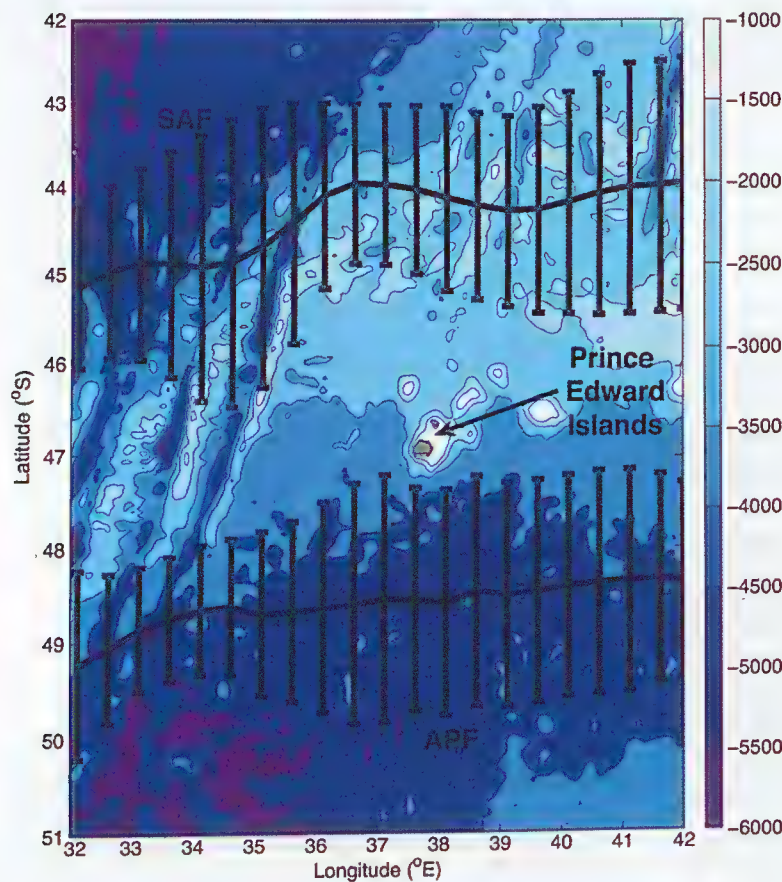


FIG. 2 — Average surface position of the Sub-Antarctic (8°C) and Antarctic Polar (4°C) fronts derived from a five-year Advanced Microwave Scanning Radiometer – Earth Observing System dataset (AMSR-E) (shown in a black line) with respect to the Prince Edward Island group. The error bars indicate the extent of the respective fronts within one standard deviation. Bottom topography is also shown in metres.

in water retention over the inter-island region encouraging algal bloom development (Perissinotto & Duncombe Rae 1990). During these periods, signature Antarctic species along with many typical APFZ species, suggest that water typical of modified Antarctic Surface Water dominates this region. In contrast, when the SAF meanders southwards and thus in closer proximity to the islands, advection forces prevail and a flow-through system rich in both sub-Antarctic and subtropical species is established between the islands (Pakhomov *et al.* 2000b). Historical data from over 30 crossings of the SAF in the upstream region of the island group between 1959 and 1999 indicate a possible gradual southward migration in the geographic position of this front but are not conclusive (Pakhomov & Chown 2003) (fig. 3a). Nevertheless, less frequent subsurface observations in the upstream region of the Prince Edward Islands also confirm a southward shift in the SAF position (fig. 3b).

The most direct effect of a meridional shift in the SAF can be seen from changes within the species composition of the zooplankton. A review of their composition around the Prince Edward Islands indicates that over the past two decades the contribution of Antarctic species decreased by approximately 20%, whereas the number of subtropical species found in the areas had increased from 6% to 26%. This is also supported by accidental catches of subtropical fish species during the long-line fishery in the proximity of these islands (Nel pers. comm.). Although a short-term variability and eddy transport cannot be completely discounted, it may be postulated that warmer-water species have intruded into the APFZ more frequently during the past decades (fig. 4). Furthermore, it has been suggested that a southward shift in the position of the SAF would favour a through-flow regime over the island region and thus prevent bloom events from occurring (Pakhomov &

Chown 2003). Indeed, a decline in stable isotope carbon values of a bottom dwelling shrimp, *Nauticaris marionis*, indirectly postulates a decrease in the occurrence of bloom conditions in the inter-island region between the 1980s and 2000s (Pakhomov *et al.* 2004). Lastly, a decrease in chlorophyll concentrations near the islands since 1976 provides further support that a variation in the position of the SAF has occurred during the past 30 years (Pakhomov & Chown 2003).

CONCLUSION

Global climate change is expected to have substantial effects in polar ecosystems (Barnett *et al.* 2001). The study of relatively simple and ecologically sensitive systems such as the sub-Antarctic islands and their surrounding waters may be particularly useful for identifying clear responses to such changes (Bergstrom & Chown 1999). Physical data confirm that the mean sea surface temperatures at the Prince Edward Islands have increased by $>1^{\circ}\text{C}$ over the past 60 years (Melice *et al.* 2003). Mirroring this is a decrease of nearly 500 mm in precipitation, an increase of over 200 hours in sunshine and an increase in winds from the warmer sector in the Northwest (Rouault *et al.* 2005). It is unclear whether this change is expected to continue and at what rate. However, it may have already promoted long-term changes in land-based top predator populations at the islands (Crawford *et al.* 1998), possibly, through food-chain modifications (Pakhomov *et al.* 2004).

What is clear is that the entire sub-Antarctic system is in a state of flux. However, it is essential to differentiate between natural background variability and long-term trends driven by extrinsic forces such as climate change (Pakhomov & Chown 2003). Long-term research on the ocean environment of sub-Antarctic islands and in particular the Prince Edward Islands is critical if the mechanisms needed to sustain high concentrations of marine life in a changing environment are to be better understood and a unique component of the planet's biological diversity is to be conserved.

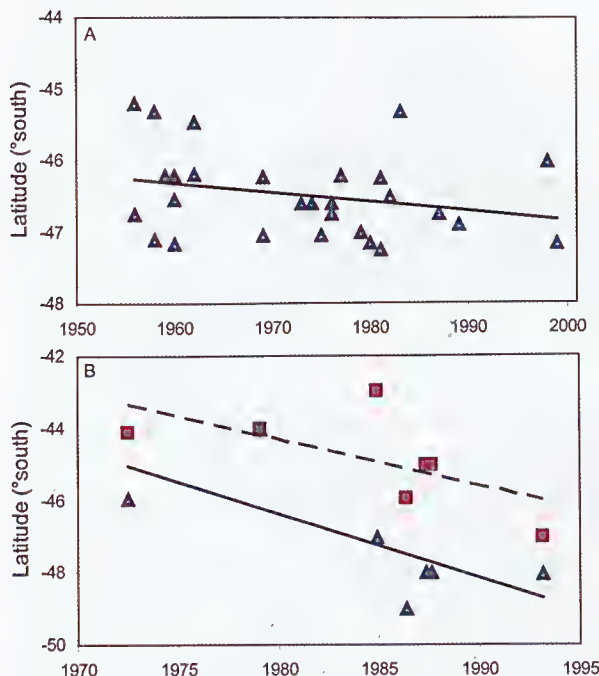


FIG. 3 — (A) Surface position of the Sub-Antarctic Front since 1955 (modified from Pakhomov & Chown 2003). (B) Subsurface expression of the Sub-Antarctic Front since 1972 in salinity (red squares) and temperature (blue triangles) (modified from Gille 2002).

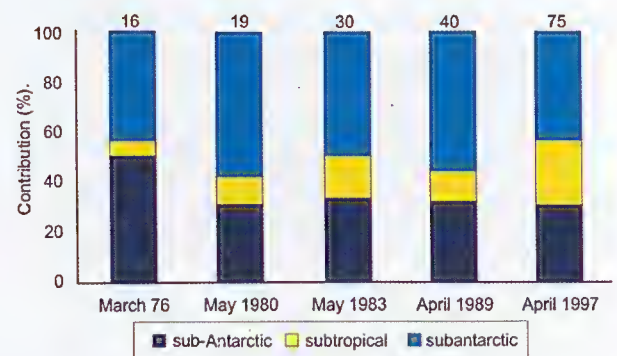


FIG. 4 — Long-term changes in the composition of zooplankton species in the vicinity of the Prince Edward Islands since March 1976 (modified from Pakhomov *et al.* 2000b).

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CHANGES IN THE SUB-ANTARCTIC IN THE MODERN ERA OF SCIENCE AND ENVIRONMENTAL CONSCIOUSNESS

by Dominic A. Hodgson

(with two plates)

Hodgson, D.A. 2009 (11:xii): Changes in the sub-Antarctic in the modern era of science and environmental consciousness. *Papers and Proceedings of the Royal Society of Tasmania* 143(2): 19–24. ISSN 0080-4703. British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge, CB3 0ET, UK. Email: daho@bas.ac.uk

This paper defines the “modern era of science and environmental consciousness” both in a global sense and, more specifically, when applied to the sub-Antarctic archipelagos. It briefly describes some key changes occurring in the sub-Antarctic terrestrial biome including climate change and the introduction of non-indigenous species. Three case studies are presented that demonstrate how important these changes are in the context of long-term natural climate and environmental variability. Finally, the role of science and environmental consciousnesses in informing future management of the sub-Antarctic islands is considered.

Key Words: sub-Antarctic, climate change, non-indigenous species, palaeoecology, management.

INTRODUCTION

The “modern era of science” in the Antarctic and sub-Antarctic is relatively easy to define as a legacy of the International Geophysical Year (IGY 1958) when many of the first systematic long-term monitoring programs were initiated and permanent scientific facilities established. It marked a partial shift in effort from economic exploitation towards systematic data gathering and scientific research.

The “modern era of environmental consciousness” is, however, a more nebulous concept. For some it is interpreted as a developing awareness of the natural world over the past c. 140 years. This has been marked by a number of pivotal events: the creation of the World’s first national park at Yellowstone in California in 1872, the publication of Rachel Carson’s *Silent Spring* in 1962 (Carson 1962), the Vietnam war, Civil Rights, Peace, and Women’s movements of the 1960s, the 1970s Earth Day and the growth of the green movement, the publication of James Lovelock’s Gaia theory in 1972 (Lovelock 2000) and, in Tasmania, the campaigns against the damming of Lake Pedder, the 1982–83 blockades to prevent damming of the Franklin River and, both in Tasmania and elsewhere, ongoing campaigns for the application of democracy to old-growth forest management.

However, when considering the sub-Antarctic, the concept of a developing environmental consciousness is not simple to apply. Accounts of the earliest expeditions suggest that the perception of their participants was that nature was something to be feared and tamed. For example, Captain James Cook’s crew variously described their discovery of South Georgia as follows: “It exceed(s) in wretchedness both Tierra del Fuego and Staten Land which places ‘till I saw this, I thought might vie with any of the works of Providence in that particular” (Charles Clerke 1775 in Beaglehole 1961, and Headland 1984, p. 29); “It is ... of less value than the smallest farmstead in England” (Anders Sparrman 1775 in Headland 1984, p. 29); and “The very thought to live here for a year fills the whole Soul with horror and despair ... charity lets me hope that human nature was never thought so low by his Maker, as to be doomed to lead or rather languish out so miserable a life” (J.R. Forster in Headland 1984, p. 29).

Attitudes to iconic species such as King Penguins, *Aptenodytes patagonicus* J.F. Miller, 1778, were hardly more charitable. George Forster, on encountering the King Penguins in Possession Bay, South Georgia, in 1775 wrote: “these birds were so dull as hardly to waddle from us; we easily overtook them by running, and knocked them down with sticks” (Headland 1984, p. 28). On Kerguelen, Captain James Cook “... found the shore ... covered with penguins and other birds, and seals. These latter were ... so insensible of fear ... that we killed as many as we chose” (Cook 1777, 24 December 1776). Even the early woodcuts by William Hodges, for example, of Possession Bay in Captain Cook’s description of the island depict a dark and foreboding scene that is far removed from the images we see of South Georgia today (Cook 1777) (see pl. 1).

Historical context is critical in shaping these perceptions. One must not forget that a number of the sub-Antarctic islands were discovered by expeditions that had set out to find the “Terra Incognita Antarctica”. Their excitement on finding land, then almost immediate disappointment on discovering it was just another island, no doubt coloured their perceptions. Added to this the deprivations experienced by expeditioners during sea voyages at that time must also be taken into account when comparing their perceptions with those of modern visitors who usually arrive in high levels of comfort and safety with at least some in a drug-induced stupor that has kept their sea sickness at bay.

By the time the islands were first systematically exploited, it can be argued that a new environmental consciousness was already well established, at least in Europe, where many of the early sealing and whaling companies were based. Here, the roots of the environmental movement had been developed by the Romantic poets: Wordsworth 1770–1850, Coleridge 1772–1834 and others who redefined nature as a thing of beauty and inspiration rather than something to be feared and tamed. At the same time many of the classical European parklands were being created by Capability Brown and his followers. However, the sealers, whalers and penguin renderers were practical men who, in all probability, did not perceive the islands through “romantic” eyes. Nevertheless, perceptions of the islands were changing; consciousness of the environment was that the islands represented new economic opportunities (to the extent that the early visitors

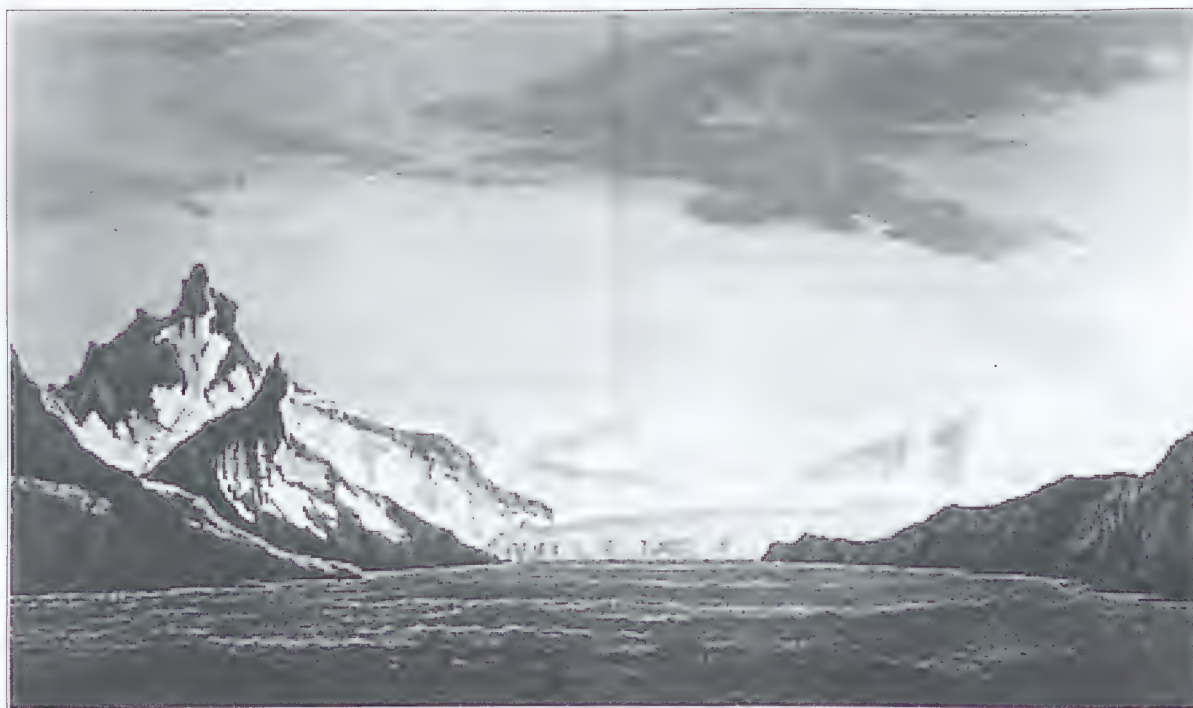


PLATE 1
Possession Bay in the Island of South Georgia, woodcut by William Hodges.



PLATE 2
Annenkov Island and Fan Lake. South Georgia can be seen on the top right of the photograph (courtesy of K. Schafer).

rarely documented their voyages so that others couldn't share in the bounty). Several waves of exploitation ensued with many of the islands' whales, fur seals, elephant seals and penguins killed for fur and blubber, with some species being hunted to near extinction (Bergstrom & Selkirk 2007). Here, poisons were applied for the first time, not to remove non-indigenous species (NIS) as occurs today, but to remove native wildlife that was interfering with the penguin oil industry. A. Hamilton at Macquarie Island notes in his 1894 diary that: "sailing about overhead were numbers of ... skua the terror of all other birds. The working party find them so destructive to the young penguins that, by means of poison, a very large number have been killed to protect the oil interest" (Hamilton 1894, p. 571). Thus, at this time environmental consciousness was centred primarily on identifying and exploiting the economic opportunities of the newly discovered islands.

Today's visitors (both tourists and scientists) clearly see the sub-Antarctic in a different way to these early pioneers, preconditioned as they are by a diet of television documentaries. For others, such as fishermen and tourism operators, the islands still represent their economic livelihood so, just as their predecessors exploited the blubber and oil, they respectively exploit the sub-Antarctic for its fish and to provide visitors with access to its natural attractions. What most visitors have in common is that they now perceive that there are threats to the natural environment. Two of the most important threats are climate change and the introduction of NIS (Bergstrom & Selkirk 2007).

CLIMATE CHANGE

With the establishment of meteorological stations on many sub-Antarctic islands, climate change is relatively easy to measure. Despite the ongoing need for a robust databank of quality-controlled sub-Antarctic meteorological data (Pendlebury & Barnes-Keoghan 2007), it is possible to calculate trends in the longer records with some confidence. For example, surface air temperature trends for Marion and Gough islands have risen at a rate of +2.8 and +0.4°C per 100 years respectively (Jacka *et al.* 2004). These temperature trends are broadly consistent with positive sea surface temperature trends in the sub-Antarctic region (Pendlebury & Barnes-Keoghan 2007). There is also variation in the months when this warming is experienced; for example, at Marion Island warming has been experienced in all months except June (Pendlebury & Barnes-Keoghan 2007), and on Macquarie Island, warming is most pronounced in late summer and early autumn, although the island cools during severe ENSO events (Frenot *et al.* 2005).

Other parameters such as precipitation have also changed. For example, at Marion Island annual precipitation has decreased since the mid-1960s, with the 1990s being the driest of the five decades that precipitation has been measured at the island (Smith 2002). Inter-annual variability in annual total sunshine hours is also large, and irregular, but a significant proportion of that variability can be ascribed to an average increase of 3.3 hours each year between 1951 and 1999 (Smith 2002, Stern 2009). A recent synopsis of climate change in the sub-Antarctic (Pendlebury & Barnes-Keoghan 2007) identifies some of the climate projections through the twenty-first century including warming across the region and a decline in precipitation extending southwards towards 50°S over much of the sub-Antarctic, though these trends are

still likely to show considerable variation at a sub-regional scale. These climate changes are predicted to have major changes on the biology of the sub-Antarctic (Bergstrom & Selkirk 2007, Convey 2006, Convey *et al.* 2006, Frenot *et al.* 2005, Smith 2007).

NON-INDIGENOUS SPECIES

The threat of NIS involves both the existing consequences of NIS already established on the islands and the consequences of the introduction and establishment of new ones (Frenot *et al.* 2005, Smith 2007). Numbers of NIS are often difficult to determine, but often their impacts are relatively easy to measure. NIS were often introduced as a way of keeping a ready store of food in the event of forced stays on the islands (European Rabbits, *Oryctolagus cuniculus* (Linnaeus, 1758), Reindeer, *Rangifer tarandus* Linnaeus, 1758, Cattle, *Bos taurus*, Linnaeus, 1758, Pigs, *Sus scrofa* Linnaeus, 1758, to make the islands feel more like home or control other pests (Domestic Cats, *Felis catus* Linnaeus, 1758), and accidentally through ships' cargo movements and shipwrecks (rodents). Sometimes even the exact date of introduction is known. For example, on 22 October 1874 naval officer Cyril Corbet, part of an expedition that set out to observe the transit of Venus at Îles Kerguelen (49°20'S), stopped at Robben Island (near Cape Town) to collect 150 European Rabbits and on arrival at Kerguelen, noted in his diary that: "a hole being dug in the hill-side, the bottom of the box was knocked out, and the poor little things left to burrow if they liked; but I'm afraid they have not a chance against these molyhawks and these other sea birds that also live in holes in the ground" (Corbet 1875, p. 60). History has proved him quite wrong in this prediction! The impacts of NIS, including humans, are widespread in the sub-Antarctic. These impacts have been recently reviewed by Bergstrom & Selkirk (2007), Smith (2007) and Convey (2008).

ASSESSING THE IMPACTS OF CLIMATE CHANGE AND NIS

Although the impacts of climate change and NIS are considered tangible threats to the sub-Antarctic terrestrial biome, it is important to judge their impacts within the context of long-term natural variability.

In order to define natural variability it is usually necessary to look beyond the instrumental measurements that began during the IGY (and occasionally before). Here geomorphological evidence and palaeoecological records can provide an invaluable longer term perspective, although it remains a challenge to provide unequivocal baseline descriptions of "unmodified" sub-Antarctic ecosystems, in either the marine or terrestrial realms. Such studies show that there are considerable variations in the impacts of climate change and NIS on different islands. For example, that there are islands where no change (outside of the range of natural variability) has occurred, islands where the combined impact of climate change and NIS are more significant than either in isolation, and other islands where recent impacts of NIS likely exceed all measures of natural ecological variability on millennial timescales. Examples of these progressive degrees of impact are described below.

An example of an island that has experienced few or no detectable recent impacts from climate change and NIS is

Annenkov Island, just off the south coast of South Georgia (pl. 2). Here, a 5 m lake sediment core has been drilled into 18 m-deep Fan Lake and analysed for its sedimentology and biological fossils for a period spanning more than 7850 years (Hodgson unpubl. data). What is remarkable about this record is the absence of any floristic changes in the diatom communities (which are sensitive indicators of environmental change) in the past 200 years that are outside of the range of natural variability. Annenkov Island, like a number of the smaller offshore islands in the sub-Antarctic archipelagos, has remained, to the best of our knowledge, free of NIS and to date the reconstructions of its past environments suggest that it has not yet experienced any measurable ecological effects from recent directional climate change. However, like other islands in the South Georgia archipelago, the island is not immune to sporadic visits and indirect human activities, and, like other islands, is subject to the adverse effects of long-line fishing practices which are responsible for the rapid decline in some albatross populations. The first monitoring of these populations has been carried out on Annenkov Island and other islands in the South Georgia archipelago (e.g., Poncet *et al.* 2006), and future surveys will be able to establish if any systematic changes are taking place.

An example of an island which is currently experiencing the combined impacts of both NIS and climate change is the mainland of South Georgia. High-latitude glaciers are known to respond to climate changes, with the majority retreating at times of increasing temperature (A.J. Cook *et al.* 2005). Recent measurements on South Georgia from historical aerial photography and satellite data show that of over 100 coastal glaciers on South Georgia 97% have retreated from the 1950s to the present and that the rate of retreat is accelerating (A. Cook unpubl. data). But how significant is this? Multi-beam bathymetric surveys of the topography of the seabed around South Georgia show that in the past glaciers have extended as far as the edge of the continental shelf more than 50 km offshore occupying substantial glacial troughs to the north and south of the island (Graham *et al.* 2008). In the context of these substantial historical changes the oscillations of the past few decades would appear to be relatively minor. Moreover, the indigenous flora would appear to be well adapted to glacial expansions and contractions with many elements surviving through the glacial cycles (Van der Putten 2008). What is different now is that the introduction of NIS on the island, particularly Norway Rats (Brown Rats), *Rattus norvegicus* (Berkenhout, 1769), has made the implications of these glacial changes potentially catastrophic for some elements of the biota. Why? We know from observations that the presence of rats has decimated some populations of birds including the South Georgia Pipit, *Anthus antarcticus* Cabanis, 1884, which is endemic to the South Georgia archipelago. Here, the remaining tidewater glaciers extend into the sea and protect the remaining population of c. 3000–4000 pairs in a few mainland areas, the rest being confined to c. 20 small, rat-free offshore islands and islets (<10% of total habitat). For this and other ground-nesting and burrowing birds the glaciers afford essential protection to the mainland populations whilst the offshore islands provide a final refuge (A. Cook unpubl. data).

What the measurements of accelerating rates of glacial retreat tell us is that soon, many of these tidewater glaciers will retreat up their feeder valleys and there will be no impediment to the rats (and other species such as Reindeer

and House Mice, *Mus musculus* Linnaeus, 1758) occupying the few remaining parts of the island that are not currently impacted, leading to the degradation of the mainland native flora and fauna (A. Cook unpubl. data). Thus, the accelerating retreat of the glaciers, which on its own would have had a negligible, if not positive, impact on the island's wildlife, is now set to be the catalyst for further destruction. In this case the combined impacts of climate change and NIS will have a far greater impact than either factor in isolation.

A final example again concerns NIS, but in this case their distribution has remained unchecked by natural barriers. Macquarie Island, halfway between Australia and Antarctica, was discovered in 1810. As with many other sub-Antarctic islands, rodents invaded the island from ships' cargo movements and shipwrecks. Cats were then introduced to keep the rodents under control; European Rabbits were then added to give shipwrecked sailors and visitors something to eat. Until recently little has been known about the natural variability of the island's climate and vegetation prior to human arrival, so it has been difficult to assess the extent to which the recent impacts of these NIS compare with past natural environmental changes.

Palaeolimnological studies are being used to assess this. Sediment cores have been collected from lakes on the island, and when analysed will reveal to what extent the environmental changes taking place exceed those that might have occurred naturally. The first results suggest that the impacts of NIS might exceed all natural changes of the past few thousand years. For example, in one of the lakes studied, sedimentation rates have increased by two orders of magnitude in the past 200 years as a result of catchment slope instability presumably brought about by the burrowing and grazing activities of the rabbits. The dominant diatom species in the lake have also changed. Collectively this suggests that a regime shift has occurred in the lake ecosystem and lake catchment which is unprecedented in the Holocene (K. Saunders unpubl. data). Modern geomorphological mapping is also revealing the extent of the slope instability and erosion from the burrowing activities of NIS, and vegetation mapping is revealing the spatial pattern of vegetation change and the distribution of non-indigenous plant species (Bergstrom *et al.* 2009). Wildlife monitoring has documented the extinction of two endemic flightless birds, a rail and a parakeet, both extinctions attributed to humans and NIS. In this example of an island with no barriers to the distribution of NIS it appears that the impacts of NIS far outweigh any impacts that have occurred as a result of both millennial-scale and recent climate changes.

THE IMPORTANCE OF THE SCIENTIFIC ERA

In these three brief case studies, different degrees of intervention continue to be required if the islands are to be well managed in the future. Management plans are in place for most of the major sub-Antarctic islands and these are reviewed regularly. However, the objectives and principles of these management plans have yet to be more generally defined for the entire sub-Antarctic region on decadal to centennial time scales because, as shown above, these are influenced by the changing state of "environmental consciousness". This not only differs between individuals and the organisations and nations that they represent, but also has changed quite radically since less than a century ago. It is therefore

possibly naive to think that a century from now they won't have changed quite substantially again. Fundamentally, it is not uniformly agreed for what the sub-Antarctic islands are being managed. Are they to be preserved, or conserved? How much economic exploitation is acceptable? What role should tourism play? Although most managers today would cite some form of conservation as their goal the answers to these questions differ subtly between management plans and unlike the Antarctic Treaty Area, are not underwritten by any single multilateral agreement.

These questions will continue to be debated. But what has changed since the IGY is that we now have scientific data to inform our management. Complementary long-term records archived in lake, terrestrial and marine sediments are now, on some islands, extending this instrumental record back thousands of years. Critically this means that many of the changes now taking place in the sub-Antarctic biome can be measured against pre-human impact status and long-term natural variability. It is apparent from these scientific data that islands such as Annenkov Island, Bird Island, Heard Island, Prince Edward Island, and some of the minor islands of the sub-Antarctic archipelagos are now the most appropriate places to meet preservation objectives, where the ancient biomes of the sub-Antarctic still, to a varied extent, survive. In December 2008 a team of researchers visited Prince Edward Island 20 km northeast of the much larger Marion Island for a week and "enjoyed noticing the abundance of spiders and caterpillars crawling through our tents and over our shoes, and the noise of burrowing birds calling all night. This does not occur on Marion Island due to the legacy of cats and mice" (Shaw 2009, p.9). However, preservation aims must be tempered by the reality that all systems will change, with or without human intervention. Natural colonisation will occur and in the absence of agreed rules as to how to identify a NIS, it is hard to define what you do with them. For example, during the 2003–04 austral summer a single specimen of the plant *Leptinella plumosa* Hook.f. (Asteraceae) was reported having likely arrived via natural means with a seabird, or via human mediated dispersal on Heard Island, and this raises interesting ethical and management issues for the degree of intervention required and the ongoing management of the island (Turner *et al.* 2006).

Where conservation and remediation is the aim, for example on Macquarie Island, detailed vegetation mapping and wildlife surveys are now permitting thorough assessments of the response of the islands' flora and fauna to the ongoing NIS eradication programs (Bergstrom *et al.* 2009), and the dangers of unintended consequences. For example, on Macquarie Island vegetation mapping has identified enhanced damage by rabbits following the successful eradication of cats, demonstrating the complexity of managing islands with an NIS problem and the need for well-defined long-term objectives to be built into management plans. Palaeolimnological and palaeoecological studies will also enable the efficacy of these programs to be judged in the context of the longer term historical record, and benchmarked against natural baselines and natural variability. On South Georgia, satellite-based monitoring of the retreat of the tidewater glaciers has revealed the imminent danger of the rat population extending its range.

Where economic objectives exist, for example on islands such as South Georgia, the relentless exploitation of the penguin, seal and whaling stocks to the point of economic collapse has now been replaced by a fisheries management

informed by scientific data gathering and including real time computer modelling of fish stocks and fishing effort. If this continues to be successfully applied, and illegal fishing brought under control, then a long-term sustainable fishery might result. Economic tourism is also being monitored to a limited extent with surveys and scientific data being gathered on impacts of visitors on vegetation and wildlife from which the overall potential impact of the industry could in principle be better managed. In all these examples the "modern era of science" has put managers in a position where they can choose to be well informed by objective data (Frenot *et al.* 2005, Tejedo *et al.* 2009, Tin *et al.* 2009).

CONCLUSIONS

When invited to present this paper my mandate was to discuss "changes in the sub-Antarctic in the modern era of science and environmental consciousness". I have shown that "environmental consciousness" is a difficult concept to define, and is different between individuals and organisations, and changes substantially over time. Although in some parts of Western society there has been a growing awareness of the need for environmental conservation since the mid-1800s this has generally been a view held by minorities. Until relatively recently, environmental consciousness has not been applied in a consistent way to the sub-Antarctic biome which has experienced successive waves of economic exploitation and, latterly, with the development of management plans, varied efforts at conservation and preservation. What can be defined, though, is the "era of science". This has, particularly since the IGY, provided data that enable us, for the first time, to manage and exploit the islands with knowledge of their past variability, precise measurements of our direct and indirect impacts (climate change, NIS, economic exploitation) and informed forecasts of the nature and direction of future environmental changes. With this post-IGY legacy of science, the tools have been made available for the development and implementation of scientifically-informed management plans and an empirical route to good custodianship. It remains to be seen if we will use them.

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THE IMPORTANCE OF INTEGRATING SCIENCE AND MANAGEMENT: LESSONS FROM TERRESTRIAL VEGETATION CHANGE ON MACQUARIE AND HEARD ISLANDS

by J. B. Kirkpatrick

(with one plate)

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Scientific observations have demonstrated massive changes in tall tussock and megaherb cover on Macquarie Island, substantial colonisation of bare ground by native vegetation on Heard Island, expansion of the range of *Poa annua* on Heard Island, and local changes in vegetation associated with changes in the locations of animal aggregations. Suggested recent declines in *Sphagnum* and *Azorella* on Macquarie Island may have occurred but are yet to be proven. Climate change seems certain to have been responsible for vegetation expansion on Heard Island, but its role on Macquarie Island is less clear. The role of variation in rabbit populations on Macquarie Island in causing changes in the areas of vegetation dominated by tall tussocks and megaherbs is scientifically well-established. However, the relative contribution of variation in cat populations, variation in the effectiveness of the *Myxoma* virus and climate change on variation in rabbit populations has been the subject of unresolvable differences in scientific opinion. While science has been generally productive in determining needs for vegetation management and its appropriate course when needed, the bureaucratic separation of managers and scientists within Tasmania, and an emphasis on peer review and strategic research within the Australian Antarctic Division, have contributed to some fracturing of management-related science in the twenty-first century, and have resulted in scientific publication and publicity that has criticised, rather than supported, appropriate conservation management. Long-term involvement of individual scientists in both research and management planning seems to have been a key driver of good nature conservation. A renewed focus on the integration of science and management is recommended.

Key Words: bioturbation, cats, climate change, exotic plant invasion, Heard Island, management, Macquarie Island, myxomatosis, rabbits, science, vegetation change.

INTRODUCTION

Most of the claimants of Antarctic territories have undisputed ownership of at least one of the sub-Antarctic islands. The scientific programs they use to reinforce their claims on Antarctica can have a strong sub-Antarctic component, as in the case of Australia. Although future access to resources is likely to be the main underlying reason for the existence of the current extremely expensive research programs, the public rationale is based on science, in particular, science directed to improving management for nature conservation and sustainability at all of the local, regional and global scales (Frenot 2007).

Several of the sub-Antarctic islands are on the World Heritage List because of their natural values (Jackson 2007), and all are now managed primarily for nature conservation, with some, such as Macquarie Island, also attracting tourism operations (Landau 2007).

The present paper uses the two largest Australian sub-Antarctic islands, Heard and Macquarie, to explore the relationships between scientific research and nature conservation management. Macquarie Island is currently among the most human-disturbed of the sub-Antarctic islands, while Heard Island is among the least modified by direct human activity. Both have World Heritage status. The discussion is concentrated on change in the scientifically best-known element of terrestrial ecosystems, the vegetation.

VEGETATION CONSERVATION AND SCIENCE

The sub-Antarctic islands would seem, on the surface, to be ideal places to maintain or restore natural vegetation. They had no indigenous people, their history of human interference is measured in decades, rather than millennia, and most of the native components of their vegetation are well-known. However, the scientific explorers arrived after the sealers and whalers, making an understanding of the pre-human vegetation cover more difficult than it otherwise could have been. Also, the vegetation of today is part of a sub-Antarctic ecosystem with characteristics that differ markedly from the pre-human condition. Climates are different, introduced species of plants intermix with natives, and the fauna that utilises the islands is different in composition and relative abundance from the pre-human fauna.

Kirkpatrick & Kiernan (2006) have argued that nature conservation management of any reserve should concentrate on the elements of biodiversity and geodiversity that are most dependent on that reserve. This approach values the maintenance of variety in nature on the planet as a whole, not just in the area of interest. It differs from the more widely adopted approach, which is to use management to try to achieve a state which more closely resembles the pre-human condition.

Scientific research can be idiographic, concerned with describing nature, or nomothetic, concerned with testing hypotheses of causation. The first approach is inductive, the second deductive. Both types of science can provide

important information for the conservation management of vegetation.

Idiographic research determines what is what, how these “whats” vary through space, how whats vary through time and the relationships between the various whats. Management responses should be considered when idiographic research indicates that a potentially deleterious change is underway. Also, the priorities for management may change as a result of idiographic research. For example, the research that resulted in the declaration of *Azorella macquariensis* Orch. as a Macquarie Island endemic makes it legally a more important taxon to sustain than in its previous manifestation as the circumaustral *A. selago* Hook.f.

To work out whether a management response to a potentially deleterious change is possible, and, if possible, which approach is likely to be the most effective, it helps if causation is understood. The nomothetic approach does not pretend to be able to determine the absolute truth of causation, but can be highly effective in eliminating potential causes, sometimes leaving but one hypothesis. In practice, much research integrates both approaches. Hypotheses and models often arise from inductive scientific observations and can be unintentionally invalidated by idiographic work.

The results of scientific research vary in their certainty, which is rarely, if ever, total. The study of vegetation change is no exception to this general rule of variation in certainty. There are substantial observation errors associated with all forms of data used for change detection. The sampling strategy, if any, can strongly influence confidence in results, as can the coverage of time and space. Vegetation can change cyclically or chaotically as well as directionally, and cycles can vary in periodicity.

The different techniques for obtaining vegetation change data vary in their discriminatory powers and their potential for spatial and temporal coverage. The longest temporal cover can be obtained from deposits of pollen and macrofossils in their sedimentary context. Historical descriptions, oblique photographs and paintings, vertical aerial photographs, satellite digital data and permanent plots can provide data for temporal analysis of vegetation change. Wide spatial coverage can be easily obtained from satellite digital data, although, in the sub-Antarctic, persistent cloud cover makes their useful temporal incidence extremely sporadic. Vertical aerial photographs have been rare on the Australian sub-Antarctic islands for the same reason, and because there have been very few flights over them. Early oblique photographs were taken for other reasons than monitoring of vegetation change until the late decades of the twentieth century, so have poor spatial coverage before the mid-twentieth century. Similarly, permanent plots are a recent development, as well as being highly labour intensive. In an environment where organic material readily accumulates, macrofossils have potentially good spatial cover, but the labour input has mitigated against their widespread use.

VEGETATION CHANGE

The vegetation pre-1900

Holocene pollen and macrofossil sequences have been analysed from several locations on Macquarie Island (Selkirk *et al.* 1983, Bergstrom 1986, Selkirk *et al.* 1988). These indicate no major changes in the flora or vegetation cover throughout the Holocene until humans arrived on the island in 1810,

and do not indicate any great impact after this date, possibly because the sites were located well within the tall tussock and megaherb vegetation of the coastal slopes. In contrast, diatom and sediment data from an inland lake indicate sharp environmental change associated with the arrival of human beings (Saunders 2008).

Our only accounts of the vegetation of Macquarie Island in the nineteenth century post-date European Rabbit, *Oryctolagus cuniculus* (Linnaeus, 1758), introduction, which is reputed to have occurred in 1878 (Cumpston 1968). J.H. Scott (1882) noted swarms of rabbits feeding on the fleshy roots of *Pleurophyllum hookeri* Buchan. at the northern end of the island during his visit in late 1880. At this very early stage of rabbit invasion he described the vegetation of the island viewed from the sea: “... what vegetation there is has a great deal of sameness, long stretches of yellowish tussock, with occasional great patches of the bright green *Stilbocarpa polaris*, or of the peculiar sage-green *Pleurophyllum*. These with the rich brown mosses near the hill-tops are all that strike the eye ...” (J.H. Scott 1882, pp. 486–487).

More than a decade later, Hamilton (1894, p. 584) described an altitudinal transect from Lusitania Bay: “Immediately behind ... the sloping terrace [was] covered with a huge tussock grass. This grass [*Poa foliosa*] forms a huge stool, behind which there is usually a muddy pool ... Once beyond the belt of swamp ... you struggle and wrestle with the huge leaves of the Macquarie Island cabbage [*Stilbocarpa polaris*] ... The tussocks and the *Stilbocarpa* become smaller as you ascend, and at about 300 ft you gain a plateau so swept by the antarctic gales that vegetation is reduced to compact closely-growing mosses, small *Uncinias*, and the conspicuous cushion-like masses of *Azorella selago*. ... Round the tops of the hills the wind has cut out wonderful terraces from a few inches to a foot or two in height, with completely bare rock much disintegrated by the weather on the top. In some of the more sheltered places or gullies stunted plants of *Stilbocarpa* and *Pleurophyllum* cover the ground.” This description does not seem consistent with the types of rabbit damage recorded by later observers, so may also act as an indicator of the pre-human vegetation patterns on Macquarie Island.

There are no published fossil plant data from Heard Island, nor any nineteenth-century vegetation descriptions. However, the present vegetation is among the most “natural” on the planet, with only one known alien plant species, *Poa annua* L. (J.J. Scott 1989, Scott & Bergstrom 2006).

Changes in tall tussock and megaherb cover

Taylor (1955) observed a rabbit grazing front on Macquarie Island, where the rabbits “strip a small area completely before moving on” (p. 96), leaving some patches totally ungrazed. The grazing occurred on the steep coastal slopes, where Taylor (1955) observed and photographed what he thought were grazing-induced land slips. There is little doubt that the rabbits had been moving around the island, with the tall tussock and megaherb vegetation at least partially recovering its structure between grazing events (Sobey *et al.* 1973, J.J. Scott 1988). For example, Taylor (1955) believed that the rabbits had not reached the northern end of the island, where J.H. Scott (1882) had observed “swarms” eating *Pleurophyllum* in 1880. Taylor (1955) and Costin & Moore (1960) were pessimistic about the future of the vegetation of the island with continued rabbit grazing, given their observations of

putatively rabbit-induced mortality of tall grass tussocks and megaherbs. They had no temporal data apart from a few photographs taken during earlier expeditions, such as the 1911–14 Australasian Antarctic Expedition (Mawson 1943), so relied on substituting space for time in coming to this dire conclusion.

The decline of megaherbs and tussocks reversed in the 1980s and 1990s coincident with a marked decline in rabbit populations after the effective introduction of *Myxoma*, the reversal being well-documented by data from permanent plots (Copson & Whinam 1998, Scott & Kirkpatrick 2008). By 2003, tall tussocks and megaherbs were again in decline (Scott & Kirkpatrick 2008). By 2007, they were dead or decrepit over much of the island (Carmichael 2007, Scott & Kirkpatrick 2008, Bergstrom *et al.* 2009), a reliable conclusion based on repeat photography, satellite remote sensing and some permanent plot data. The possible causes of this latter decline are discussed in the next section.

Changes in megaherb and tall tussock cover have also been observed in places where animal populations were known, or thought, to have changed, or human settlement abandoned. Devegetation, and intertussock erosion of *Poa foliosa* (Hook.f.) Hook.f. grassland, at Bauer Bay was suggested by Taylor (1955) to probably be associated with an increase in numbers of Southern Elephant Seals *Mirounga leonina* (Linnaeus, 1758), since 1922. A large King Penguin, *Aptenodytes patagonicus* J.F. Miller, 1778, rookery on the Isthmus was exterminated by the sealers in the middle of the nineteenth century (Mawson 1943), with no signs of it in the tussock vegetation in photographs taken in 1911 (Taylor 1955). Some of this vegetation was destroyed by the establishment of the ANARE Scientific Station in 1948. The vegetation at the sealing settlements (1810–1922) on Macquarie Island had recovered by 1951, except for a concentration of the introduced herb, *Stellaria media* (L.) Cyrillo (Taylor 1955). On Heard Island, the abandoned ANARE station was partially colonised by megaherbs (Whinam *et al.* 2004).

Most communities, including some with tussock (*Poa cookii* (Hook.f.) Hook.f.) and the megaherb *Pringlea antiscorbutica* T.Anderson ex Hook.f., expanded their areas on Heard Island between 1947 and 2003 (J.J. Scott 1990, Scott & Bergstrom 2006). Changes in the area of vegetation cover are apparent from sequential remote sensing images, large numbers of repeated oblique photographs and some repeat sampling of vegetation at relocatable plots (J.J. Scott 1989, 1990).

Invasion by alien plants

The introduced plant species *Cerastium fontanum* Baumg., *Stellaria media* and *Poa annua* have long been established on Macquarie Island (Taylor 1955), with *P. annua* being the only known exotic plant on Heard Island (Scott & Kirkpatrick 2005). The exotics are widespread in disturbed areas below the fjaeldmark zone on Macquarie Island. *Poa annua* extended its range on Heard Island between 1987 and 2004 (Scott & Kirkpatrick 2005, J.J. Scott pers. comm.). The circum-Antarctic species *Leptinella plumosa* Hook.f. was collected for the first time on Heard Island in the 2003/2004 summer (Turner *et al.* 2006). It is impossible to tell how long it had been present on the island, as absence is harder to prove than presence, especially where botanical exploration has been very limited. However, the balance of the evidence suggests recent introduction by seabirds (Turner *et al.* 2006). Seabirds

may have also been responsible for introducing *P. annua* to Heard Island (Scott & Kirkpatrick 2005).

Other vegetation changes on Macquarie Island

The waning, waxing and waning of tall tussock and megaherb cover on Macquarie Island has had implications for associated species of lesser stature, well-documented in the literature (Taylor 1955, Copson & Whinam 1998, Kirkpatrick & Scott 2002, Scott & Kirkpatrick 2008, Bergstrom *et al.* 2009). Recent changes in *Sphagnum* and *Azorella* cover have been suggested to have also occurred on Macquarie Island.

Whinam & Copson (2006) presented evidence that they interpreted to show that *Sphagnum* had suffered a recent decline on Macquarie Island. They observed the size and number of patches of *Sphagnum falciculatum* Besch. in November 1992, November 1996, November 1998, November 1999 and March 2004. They used 23 patches, 16 of which were measured in November 1992 and one of which was not measured until November 1998. It is possible to calculate mean annual percentage loss of number of patches between measurement dates from the data in their Table 1. This rate was 7.81% between 1992 and 1996, 5.88% between 1996 and 1998, 18.75% between 1998 and 1999, and 4.97% between November 1999 and March 2004. However, between 1998 and 1999 one patch that had previously disappeared returned out of seven that could have returned (14.28% per annum), with two patches out of nine (5.23% per annum) doing the same between November 1999 and March 2004. Because of this dynamism in a context in which the measurements were of selected patches, not of all patches within areas, it is difficult to tell from the data to what degree *Sphagnum* patches on the island were increasing or decreasing in number and/or size between measurement times, although the higher annual rate of return than loss between 1999 and 2004 appears more consistent with an increase in this period than the posited decrease.

The 1992 and 1996 repeat photographs (figs 2 and 3 in Whinam & Copson 2006) conclusively show an increase in number and size of *Sphagnum* patches at Green Gorge. It may be possible to use later repeat photographs to come to firm conclusions on the temporal patterns of change in this vegetation type, but these probably would need to be annual given the large variations in the magnitude of changes in numbers of patches summarised above.

During the 2008/2009 summer, scientists and managers observed widespread dieback in *Azorella macquariensis*, with those on repeat visits having the strong impression that this was a new phenomenon (J.J. Scott, pers. comm.). However, there have been some previous observations of dieback in the species. Taylor (1955) observed rabbits digging conspicuous ‘squats’ in *Azorella* cushions. The genus *Azorella* is also known to be eaten by rabbits (Chapuis *et al.* 2004). Taylor also noted that *Azorella* leaves died back in patches in March and April, regarding the phenomenon as an aspect of their phenology (Taylor 1955). Repeat oblique photography might give some insights into the novelty of this dieback, if enough old photographs exist and the scenes can be relocated. Mapping the dieback and determining its environmental correlates would be an important first step in determining the cause and the need and potential for management of the phenomenon. Care needs to be taken in attributing dieback to putatively pathogenic organisms

on the basis of their association with dieback, as association cannot separate cause and consequence.

CAUSES OF VEGETATION CHANGE

Influences of native and introduced vertebrates

The large populations of nesting, moulting and resting native vertebrates that use both islands fertilise, defoliate and create landforms in the places they use. Changes in populations, or the locations of populations, can be clearly associated with vegetation changes, as in the examples given above. On Heard Island, the expansion of *Poa annua* was statistically associated with moulting and resting animals (Scott & Kirkpatrick 2005).

In itself, the contrast between the vegetation inside and outside the numerous rabbit enclosure plots on Macquarie Island (pl. 1) leaves no reasonable doubt that variations in the intensity of rabbit grazing have been the cause of changes in the cover of tall tussocks and megaherbs on Macquarie Island, and, therefore, of changes in the cover and abundance of taxa of lesser stature. However, the causes of variation in rabbit populations have been disputed.

The evidence for the initial effectiveness of the rabbit control program using the *Myxoma* virus and the rabbit flea is overwhelming (Copson *et al.* 1981, Brothers *et al.* 1982, Brothers & Copson 1988). The dispute relates to the relative contribution of possible causes of the resurgence of rabbit populations in the early twenty-first century. Bergstrom *et al.* (2009, p. 78) stated that: "Rabbit numbers have returned to pre-control levels and this can be clearly ascribed to the removal of cats", although they also stated that: "Higher autumn temperatures may have improved rabbit kitten survivorship up to the winter months" (Bergstrom *et al.* 2009, p. 79). They dismiss "... some speculation of reduced efficacy of the (*Myxoma*) virus" by Scott & Kirkpatrick (2008) on the grounds that: "... the impact of the *Myxoma* virus was still evident in April 2007, with numerous rabbit carcasses present at the base of coastal slopes ..." (Bergstrom *et al.* 2009, p. 79). Brothers & Bone (2008, p. 143) had earlier expressed a very different opinion: "Ongoing control [of rabbits] was compromised by the failure to ensure supplies of *Myxoma* virus to maintain an effective inoculation program. Any perception that cat eradication was somehow a catalyst for the rabbit population increase that subsequently occurred is erroneous and most convincingly disputed by the historical trends in rabbit abundance on the island irrespective of cat numbers through that time (Copson *et al.* 1981, Copson



PLATE 1

An enclosure on Macquarie Island established by Geof Copson in 1975 (Copson & Whinam 1998). The photo was taken in 2009, after the rabbit population explosion of the early twenty-first century. *Stilbocarpa polaris* (Hombr. & Jacquinot ex Hook.f.) A. Gray dominates within the enclosure, but is absent outside (photograph: J.J. Scott).

2004). Cat predation on rabbits has never been sufficient to regulate rabbit numbers, which is not surprising considering that there were only ever known to be approximately 250 cats on the island (Brothers *et al.* 1985)."

The models on which the conclusion of Bergstrom *et al.* (2009) was based treated cats as a qualitative variable, despite the fact that numbers plummeted to zero between 1998 and 2001 in the course of the extermination campaign, and ignored the evidence of reduced efficacy of the *Myxoma* control program, treating *Myxoma* as a constant. The use-by date of the last of the *Myxoma* vials (2002) is a better fit to the rabbit resurgence than the death of the last cat (2001), even if one were prepared to ignore the pre-*Myxoma* history of the interaction between rabbits and cats, which one logically should not. The fact that cats were on Macquarie island 60 years before rabbits, and the subsequent co-existence of both cats and rabbits, suggests that cat predation alone could not keep the population of rabbits down to a level equivalent to that of the 1980s and 1990s, during which *Myxoma* use was at its height and the rabbit population was comparatively reduced. However, some contribution of cat extermination to the rabbit population explosion may have occurred (Carmichael 2007, Scott & Kirkpatrick 2008). The data available simply do not allow a disentanglement of the contributions of potential causes of the recent explosion in rabbit numbers.

The activities of *Homo sapiens* can cause defoliation, either extreme, as in the case of the construction of scientific stations, or mild, as in the case of trampling damage (Scott & Kirkpatrick 1994). The major future impacts of *H. sapiens* on the vegetation of the two islands are likely to be through unintentional introduction of exotic organisms, the ecosystem effects of the exploitation of marine species in the Southern Ocean and the global effects of air pollution caused by humans on climate (Whinam *et al.* 2005, Whinam *et al.* 2006, Bergstrom & Selkirk 2007).

Climate change

Although the climatic data for Heard Island are inferior to those available for Macquarie Island, the effects of climate change on vegetation change are much more verifiable. Annual average temperature at Atlas Cove on Heard Island was approximately 1°C higher in the period 1997–2001 than between 1948 and 1954 (Thost & Allison 2006). Glaciers reduced in area on Heard Island from c. 290 km² to c. 260 km² between the early 1940s and the late 1980s (Ruddell 2006) and have continued to recede, presenting new land for the colonisation of plants, an opportunity that has been taken, at least between 1987 and 2004 (Scott & Kirkpatrick 2005, Scott & Bergstrom 2006).

On Macquarie Island, temperatures increased by approximately 1°C between the 1940s and the late 1970s, but have remained stable since (Pendlebury & Barnes-Keoghan 2007), during a period in which annual rainfall and the number of days with rainfall greater than 6 mm showed a tendency to increase (Brothers & Bone 2008). The figure of 6 mm is significant because it is a possible threshold for burrow flooding, which certainly occurs when this amount of rain occurs two days in a row (Brothers & Bone 2008). Heavy rainfalls are also associated with land slips (Selkirk 1996). Brothers & Bone (2008) suggested that rabbits may have relocated their burrows from their previous locations on more gently sloping land to the better-drained tall tussock-covered slopes in response to more frequent

burrow flooding events and that, in the absence of effective control through myxomatosis, increased populations had defoliated these areas. They refer to Tasmanian Parks and Wildlife Service unpublished records to reject alternative hypotheses of increased immunity to the disease and a prolonged breeding season related to drier winters.

If some relocation of rabbit burrows to the tall tussock-covered slopes occurred between 1981 and 1995 when rabbit numbers were very low overall, there could have been grazing-related minor thinning of tall tussocks and consequent increases in plant species richness. These changes occurred on apparently ungrazed plots on the slopes in this period and were attributed to endogenous processes (Kirkpatrick & Scott 2002).

Drier conditions resulting from stronger winds have been suggested as the cause of the putative loss of *Sphagnum*-dominated vegetation on Macquarie Island since 1996 (Whinam & Copson 2006). However, the contradiction between the rainfall record and supposed drying has yet to be satisfactorily resolved. One area that may merit investigation is the role of tall tussocks and megaherbs in fog drip. Their destruction by rabbits could have resulted in less moisture reaching the soil. In the Australian Alps, a much less misty environment than Macquarie Island, 3–7% of precipitation comes from fog drip (Costin & Wimbush 1961).

INTERACTIONS BETWEEN SCIENCE AND MANAGEMENT

Macquarie Island was primarily managed as a scientific station between 1948 and the early 1970s. Scientists employed by the Commonwealth, such as Bill Taylor (Taylor 1955), and those visiting to undertake research, such as Alec Costin (Costin & Moore 1960), raised scientific and bureaucratic awareness of the vegetation deterioration associated with rabbits on Macquarie Island. The Tasmanian Department of Agriculture, in co-operation with the CSIRO and ANARE, investigated and trialled 1080 poisoning and introduction of the *Myxoma* virus as control methods, and found neither to be effective (Sobey *et al.* 1973). Their solution was to introduce the European Rabbit Flea, *Spilopsyllus cuniculi* (Dale), as a vector for the virus (Sobey *et al.* 1973, Skira *et al.* 1983).

Peter Murrell, the first director of the Tasmanian National Parks and Wildlife Service (PWS), which was established in the early 1970s, took the approach that those who undertook research on wildlife species should also be responsible for developing and implementing management regimes for their conservation. From the 1970s onwards, PWS researchers/managers became regular visitors to the islands, setting up monitoring and observation programs, many of which have persisted to the present. Their observations of bird and mammal populations, and their work with permanent plots and exclosures, reinforced the earlier conclusion that rabbits were a major management problem, directly threatening native vegetation and indirectly threatening bird species. The previous establishment of the European Rabbit Flea as a vector for the *Myxoma* virus allowed PWS to introduce the virus to the scattered rabbit populations on the island, and maintain its efficacy in controlling rabbit populations by a program of continuous reintroduction (Brothers & Copson 1988). However, even in 1983, after the myxomatosis-induced crash in rabbit populations, they were in the process of investigating other means of rabbit

control, because of the lack of ubiquity of the flea (Skira *et al.* 1983).

From the 1970s onwards, one of the major responsibilities of the PWS rangers on the island was to control cats, which had been shown by earlier research to be threatening the local extinction of several bird species (Copson & Whinam 2001). PWS produced a cat eradication plan (J.J. Scott 1996), which recognised that the eradication of cats might have consequences for the populations of other pest species, but which anticipated that the current rabbit control program would continue to be effective. The cessation of production of the *Myxoma* virus in 2000 was totally unpredictable at the time. The cat eradication plan, as part of an integrated vertebrate pest management strategy (Copson & Whinam 2001), recognised cat, rabbit and rodent eradication as the desired goal, but only cat eradication as currently feasible, which it was, with all cats being killed between 1998 and 2001. Predictions of the recovery of bird populations after cat extermination were verified (Brothers & Bone 2008).

At the same time as the last *Myxoma* was produced by the Commonwealth Serum Laboratories in 2000, the integration of science and management within PWS was history, the Tasmanian State Government having bureaucratically separated its wildlife scientists from park management personnel, probably because it saw scientific input as an obstacle to tourism development (Kirkpatrick 2001). The scientific program of the part of the Commonwealth bureaucracy responsible for the Antarctic and sub-Antarctic (AAD) was also in a state of rapid transformation, from researcher-led inquiry to inquiry directed by strategic plans and tested by peer review. While the strategic plans developed by the AAD gave priority to understanding the risks presented by climate change to the biota of the sub-Antarctic islands, and consistency with the plans was a major criterion in judgement of competing projects, the other criteria related to the scientific merit of projects and investigators.

Peer review processes favour those scientists who publish prolifically in journals with high citation rates and are capable of convincingly framing their research proposals within the major strategic goals of the granting body. Journals with high citation rates publish work that breaks theoretically new ground, preferably work that uses the very latest, or novel, techniques. Research that can aid management is seldom at this rarefied level, tending more to the idiographic than the nomothetic, and to well-established and reliable techniques rather than innovative techniques. Strategic research plans are very good at addressing the historic concerns of those who control their content, but not as good as independent scientists or scientist/managers in rapidly addressing unanticipated concerns.

In 2000, fissures developed between the State government bureaucracy responsible for the management of the island and its wildlife and the AAD. This fissure was occasioned by the public controversy over the hot-iron branding of Southern Elephant Seals as part of a long-term AAD population research program (Vertigan 2007). The PWS and the permit-granting scientists, now based independently in the Department of Primary Industries, Water and Environment, became more assiduous in controlling the research activities funded by the AAD, to the degree to which some projects had to be abandoned at late notice.

In response to the resurgence of rabbit numbers from 2002 onwards, State scientists, State managers, the AAD scientists and independent scientists funded within AAD

programs independently collected data on the consequent massive vegetation changes. The unpublished results of some of the research were critical in the arguments made by independent scientists and non-government organisations for funding of the program (e.g., Scott *et al.* 2007), arguments that had to obtain an extremely high public profile before both governments would accept their responsibilities under the World Heritage Convention.

Two refereed papers on vegetation changes that resulted from the rabbit resurgence (Scott & Kirkpatrick 2008, Bergstrom *et al.* 2009) were published soon after the decision was made to fund the rabbit and rodent eradication program. The former paper resulted from the long-term monitoring work of university and independent scientists. Its publication received little media attention because the results and conclusions of the work had already been well-publicised. The authors concluded that the rabbit and rodent eradication program was well-justified and that it was not possible to ascribe the rabbit resurgence to any specific cause. The second paper reported the work of AAD and associated scientists. It was in a highly prestigious international journal, received special praise from the journal editor (Cadotte 2009) and was the subject of a large number of national and international media reports. The theoretical idea of "ecological cascades", the use of the latest remote sensing and statistical techniques, and a critique of previous management had produced a paper of great academic and popular interest. The paper concluded that State scientists and managers had inadvertently caused substantial ecological damage requiring a greater than \$A24 million rabbit and rodent eradication program by their unprescient decision to eliminate cats. The longstanding PWS plans for rabbit and rodent eradication, independent of the fate of cats (Skira *et al.* 1983, Copson 1995, J.J. Scott 1996), and the lack of convincing evidence that cat eradication was largely responsible for the rabbit population increases (as discussed above) were ignored. It was ironic that one of the best examples in the world of the use of scientific research for effective biodiversity management (the integrated pest management process) should have received such a bad international press, a press that could unfortunately make it more politically difficult in future to eradicate damaging vertebrates from other islands.

The above history and previous work (e.g., Copson & Whinam 2001, Frenot *et al.* 2005) have shown that research work has been invaluable in determining appropriate conservation management on the sub-Antarctic islands. It has also been invaluable in determining the vegetation changes that are intractable to management and those that do not require management. Vegetation changes that have resulted from global climatic change are not amenable to local management in themselves, although where climate change interacts with other more controllable factors management action may be possible (Calder & Kirkpatrick 2008). One such interaction on Heard Island and Macquarie Island is with the exotic plant species that might be able to invade as climate changes. They may be prevented from invading, using quarantine procedures developed from research on invasion processes (Whinam *et al.* 2005), or eliminated when their populations are small, as in the cases of *Anthoxanthum odoratum* L. and *Rumex crispus* L. on Macquarie Island (Copson & Whinam 2001). Decades of collection of plot data on Macquarie Island (Scott & Kirkpatrick 2008) and 13 years of observation on Heard Island (Scott & Kirkpatrick 2005) have indicated that *Poa annua* is not a threat to

native vascular plant biodiversity, which is fortunate, as its elimination would be close to impossible.

The history of the interaction of science and conservation management on Macquarie and Heard islands suggests that long-term involvement of individual scientists, especially when engaged in management planning as well as research, is one major key to success in management, if not in science, and that science has generally served conservation management well. A greater emphasis on integration of science and management and a greater financial priority for laborious data collection and monitoring activities, which provide the raw material for an understanding of any natural system, may allow the same statement to be made a decade into the future.

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ENVIRONMENTAL CHANGE AND HUMAN IMPACTS ON TERRESTRIAL ECOSYSTEMS OF THE SUB-ANTARCTIC ISLANDS BETWEEN THEIR DISCOVERY AND THE MID-TWENTIETH CENTURY

by Peter Convey and Marc Lebouvier

(with two text-figures, two tables and two plates)

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Sub-Antarctic islands share many similarities in their history of human interaction and impacts before the mid-twentieth century. Large impacts on land were associated with the marine exploitation industries of sealing and whaling. Their onshore activities involved considerable construction and pollution in many accessible landing bays, inevitably destroying large areas of coastal terrestrial habitat. Considerable transfer of nutrients to terrestrial environments will have been associated with scavengers utilising large carrion supplies. Attempted establishment of agricultural industries, particularly the introduction of grazing mammals, took place on several islands and, although rarely proving economically viable, often resulted in the long-term creation of feral populations. These were accompanied by introductions of other alien vertebrates, plants and invertebrates to most sub-Antarctic islands, although precise records of introduction events, or subsequent biological studies in this period, largely do not exist. Thus, exploitation industries in this region inevitably led to considerable alterations and impacts to terrestrial ecosystems almost from the outset of human contact with the islands. In the absence of baseline ecological and biodiversity studies, the true magnitude of many of these impacts is difficult to assess, although their legacy continues to the present day. Indeed, the almost complete removal of fur seals may have allowed coastal vegetation to become more extensive and lush than hitherto, paradoxically now regarded as “typical” and threatened by recovery of seal populations.

Key Words: non-indigenous species, nutrient transfer, habitat loss, ecosystem engineering, whaling, sealing, herbivore, predator.

INTRODUCTION

The sub-Antarctic islands lie isolated from continental landmasses in the Southern Ocean. In a terrestrial biological context, a core group of sub-Antarctic islands is often recognised, unified by general similarities in climate and the presence or absence of certain groups of flora or fauna (Selkirk 2007). This core group includes South Georgia, the Prince Edward Islands, Îles Kerguelen, Archipel Crozet, Heard and McDonald Islands, and Macquarie Island. These islands lie close to the oceanic Antarctic Polar Frontal Zone, and typically have cold, cloudy and windy climates, with limited temperature variation year-round (Smith 1984, Convey 1996, 2007a, Pendlebury & Barnes-Keoghan 2007). Only two islands (South Georgia and Heard Island) are heavily glaciated today, with Îles Kerguelen also having glaciers and an icecap in its western part. Many of these islands are currently impacted by contemporary trends of climate change (Convey 2007a, Pendlebury & Barnes-Keoghan 2007, le Roux 2008), but such impacts lie outside the scope of the current paper. The anthropogenic factors underlying current global environmental change are generally accepted to have commenced during the Industrial Revolution of the nineteenth century, and their impacts have accelerated since the second half of the twentieth century. There appears to be no suggestion of detectable impacts of this process during the earlier phases of occupation and exploitation of the sub-Antarctic islands in the nineteenth and first half of the twentieth centuries (e.g., for South Georgia see fig. 4 in Cook *et al.* unpubl., based on data extracted from Turner *et al.* 2004), although this may be largely because few appropriate research or monitoring data sets exist from this period.

A range of other islands, both south and north of this core group, are also referred to in some literature as sub- or peri-Antarctic. These include the South Sandwich, South Orkney and South Shetland archipelagos along the Scotia arc, properly forming part of the maritime Antarctic terrestrial biogeographic zone (Smith 1984, Convey 2007b), and the cool temperate Diego Ramírez Island (Chile), Île Amsterdam and Île Saint-Paul in the Indian Ocean, the Tristan da Cunha group and Gough Island in the Atlantic Ocean, and the “New Zealand shelf islands” (Antipodes, Campbell, Auckland, Bounty). The maritime Antarctic archipelagos have much reduced floral and invertebrate diversity, while the cool temperate islands differ from the “core” sub-Antarctic grouping primarily in the inclusion of significant stands of woody plants in their flora, but share with them the development of a “megaherb” flora and the lack of native terrestrial mammals. As these islands have many similarities in their history of human discovery, occupation and exploitation, all are included, where appropriate, amongst the information presented in this paper.

Sub-Antarctic floras and faunas typically do not include many taxonomic and functional groups familiar from lower latitudes. Plant communities, except on the more northern islands not included in the core sub-Antarctic grouping, do not include woody plants or species requiring insect pollination (Convey *et al.* 2006a). Megaherbs, often endemic to particular islands, are a dominant feature of many communities, whose evolution is linked with the absence of native vertebrate herbivores (Meurk *et al.* 1994, Mitchell *et al.* 1999, Convey 2007a, b). There are no native land mammals, reptiles or amphibians and very few non-marine birds. A large element of the global profile of the

sub-Antarctic islands is generated by their hosting significant populations of “charismatic” marine vertebrates (seals, penguins, albatrosses, petrels, etc; Woehler *et al.* 2001). Their native terrestrial faunas comprise primarily arthropods (mites, springtails, spiders, beetles, flies and moths, with smaller representation of some other insect groups), and tardigrades, nematodes, rotifers, enchytraeids, earthworms and molluscs (Gressitt 1970, Greenslade 2006, Convey 2007a, b). There are no large invertebrate predators, and predation is likely to be an insignificant ecological pressure in indigenous communities. While detritivores appear to numerically dominate these invertebrate communities, decay processes are slow (Slabber & Chown 2002).

Sub-Antarctic terrestrial ecosystems are simple in comparison with most ecosystems globally, and are thought to lack functional redundancy. This raises the possibility of new colonists (whether arriving by natural means or with human assistance) occupying new ecological niches, which could fundamentally change the structure and function of trophic webs. Indigenous sub-Antarctic species and communities appear to be particularly vulnerable to invading predators and species with higher competitive abilities (Frenot *et al.* 2005, 2008, Convey *et al.* 2006b).

DISCOVERY AND EXPLOITATION

Initial exploitation

The first sightings of some of the more northern islands were made during the sixteenth and seventeenth centuries. These sightings, however, did not result in landings, repeat visits, or establishment of settlements or industrial activity. For instance, there are no further sightings of South Georgia known between that of 1675 and Cook’s visit in 1775 (Headland 1984) and, while Île Amsterdam was discovered in 1522 by S. Del Cano on one of Magellan’s ships, the first known landing is attributed to W. de Vlaming in 1696 (Lebouvier & Frenot 2007). The majority of islands were discovered between the latter part of the eighteenth and the early nineteenth centuries (table 1). There is archaeological evidence on Auckland Island of earlier (c. 1200) Polynesian discovery and, possibly, settlement (Anderson 2006, 2009, Dingwall 2007).

The primary focus of those who discovered all of the sub-Antarctic islands lay with territorial and economic gain (table 1). In this context the rich marine vertebrate life of the Southern Ocean and its constituent islands was

TABLE 1
History of discovery, human occupation and major industrial uses
of various sub- and peri-Antarctic islands before c. 1950¹

	Date of discovery (discoverer)	Presence of permanent settlements in 21st century	Industrial operations and other human influences
Diego Ramírez (Chile)	1619 (Ramírez)	No	Meteorological station established 1957
South Georgia	1675 (de la Roché)	Yes	Seal and penguin hunting, whaling (land-based stations 1904–1965), research expeditions
South Sandwich Islands	1775 (Cook)	No	Sealing
South Orkney Islands	1821 (Palmer, Powell)	Yes	Sealing, whaling (land-based station, Signy Island, in 1920s), meteorology/research station (Laurie Island, est. 1903), WWII operations, subsequently research (Operation Tabarin; Falkland Islands Dependencies Survey)
South Shetland Islands	1599 (Gerritsz), 1603 (de Castilla)	Yes	Sealing, whaling (land-based station, Deception Island)
Marion and Prince Edward Islands	1663	Yes	Sealing, guano collection
Îles Kerguelen	1772 (de Kerguelen de Trémarec)	Yes	Whaling (land-based station), farming (Sheep, Mouflon, Reindeer)
Archipel Crozet	1772 (Marion-Dufresne)	Yes	Sealing, whaling, shipwrecked castaways
Île Amsterdam	1522 (Del Cano)	Yes	Farming (cattle), shipwrecked castaways
Heard and McDonald Islands	1833 (Kemp)	No	Sealing, scientific station 1947–1955, temporary scientific camps since 1955
Macquarie Island	1810 (Hasselburgh)	Yes	Seal and penguin hunting, Australian Antarctic Expedition and meteorological station 1911–1915, research station est. 1948
Antipodes Islands	1800 (Waterhouse)	Yes	Sealing, farming (cattle, failed), “castaway” depot including release of goats, evidence of earlier Polynesian presence
Auckland Islands	1806 (Bristow)	yes	Whaling, sealing, farming (flax), emergency “castaway” depots for shipwreck victims, 1868–1926, including release of rabbits, cattle, pigs and goats, cattle also temporarily farmed, evidence of earlier Polynesian presence
Bounty Islands	1788 (Bligh)	No	Sealing
Campbell Island	1810 (Hasselburgh)	Yes	Sealing, whaling, farming (sheep, cattle), “castaway” depots including release of goats, coastguard and meteorological station est. WWII, closed 1995

¹ See also Cumpston 1968, Headland 1984, McIntosh & Walton, 2000, Fell 2002, Frenot *et al.* 2005, Taylor 2006, Bergstrom & Selkirk 2007, Russ 2007, Cooper 2008, Terauds & Stewart 2008).

quickly recognised as an economic bonanza. Sealing was the first exploitation industry active in the region, with uncontrolled harvesting of fur seals for their valuable pelts following within years of each island's discovery (Trathan & Reid 2009). This quickly and inevitably brought the target stocks near to extinction and led to the demise of the industry itself at most locations by the early decades of the nineteenth century, although limited population recoveries at some locations were followed by further short periods of sealing activity later in the century (e.g., on South Georgia; Headland 1984). On South Georgia, Heard and Macquarie islands, Southern Elephant Seals, *Mirounga leonina* (Linnaeus, 1758), were exploited for their oil, as were penguins on Macquarie and Auckland islands (see also Townrow 1988).

As demand for oil increased throughout the nineteenth century, the whaling industry developed, first in the Northern Hemisphere and then in the south. At first the smaller whales (Southern Right Whale, *Eubalaena australis* (Desmoulins, 1822) and Humpback Whale, *Megaptera novaeangliae* (Borowski, 1781)) were captured but, with the invention of the harpoon gun with its explosive head in 1864 the larger rorquals could be hunted. By the early twentieth century, the construction of shore-based whaling stations on some sub- and peri-Antarctic islands (e.g., South Georgia, Îles Kerguelen, Signy Island, Deception Island, Falkland Islands) as well as the southern continents, taking advantage of high local densities of whales, led to the rapid and again uncontrolled exploitation of the stocks of great whales. Towards the end of the whaling period the entire whale was processed and rendered down while, as whales became rarer, the emphasis shifted to the development of pelagic whaling and processing at sea, heralding the closure of land-based whaling stations. The larger species were exhausted first, with over-exploitation progressively moving to smaller species (see Basberg (2004) and Hart (2006) for a history of the whaling industry on South Georgia and in the South Atlantic Falkland Islands Dependencies).

Farming

The inclement and cold climate of most sub-Antarctic islands precluded the possibility of the establishment of economically viable onshore farming industries, and no exploitation of terrestrial biological or geological resources has taken place other than the use of various marine birds for food for station staff, and the industrial-scale collection of penguins for use as fuel in whale and seal oil digesters. However, on the more northern islands (Île Amsterdam and the New Zealand shelf islands), as well as on Îles Kerguelen, there were concerted attempts at the establishment of livestock (Domestic Cattle, *Bos taurus* Linnaeus, 1758, sheep, *Ovis aries* Linnaeus, 1758), and there were occasional and unsuccessful attempts at crop cultivation on some of the New Zealand islands (table 1). In some instances livestock were effectively kept to a restricted area (e.g., paddock, offshore island), while in others they were simply allowed to roam free. Other vertebrates were deliberately introduced, at least as human commensal/companion animals, to most islands where long-term settlements were established (including industrial operations and, towards the end of the period under review, scientific research stations) (table 2). These included Domestic Dogs, *Canis familiaris* Linnaeus, 1758 (primarily as sledge dogs on the southern islands), and Domestic Cats, *Felis catus* Linnaeus, 1758, the latter then released or escaping to form

feral populations on many islands as part of abortive attempts to control expanding mouse, rat and/or European Rabbit, *Oryctolagus cuniculus* (Linnaeus, 1758), populations. Smaller numbers of stock and working animals (chickens, *Gallus gallus* Linnaeus, 1758, pigs, *Sus scrofa* Linnaeus, 1758, horses, *Equus caballus* Linnaeus, 1758) were also associated with human occupation, although generally not having any direct impact on the local environment beyond the boundaries of settlements. Significant herds of feral grazing mammals were established on South Georgia (Reindeer, *Rangifer tarandus* Linnaeus, 1758, imported originally to provide "sport" for the whaling station managers; Leader-Williams 1988), Kerguelen (Reindeer, Mouflon, *Ovis musimon* Pallas, 1762, again for sport), Île Amsterdam (cattle; Chapuis *et al.* 1994) and various of the New Zealand shelf islands (tables 1, 2). In recognition of the fact that castaway survivors of shipwrecks were a frequent feature on the more northern islands, the responsible national governments also established a network of stocked depots and huts, additionally releasing animals (including rabbits, goats, *Capra hircus* Linnaeus, 1758, pigs, cattle) on some to provide a feral source of food to assist survivors (table 1; see, for example, Fraser 1986, Allen 1997). Shipwreck survivors also exploited any available local sources of food, in particular targeting breeding birds such as penguins, although these impacts would have been minor except at a very local scale.

Inadvertent introductions

An associated impact of the requirements to support these livestock, and supply the human community, was the import of animal fodder, human foodstuffs and vast quantities of general cargo. Although the risks and possible consequences were not appreciated at the time, inevitably this led to the import and subsequent establishment of a wide range of non-indigenous terrestrial invertebrates and plants. Even today it remains virtually impossible to detect the majority of such introduction events as they occur. Thus it is not surprising that there is no documentation or study of these non-indigenous species and their impacts prior to the mid-twentieth century. It seems likely that many of the c. 200 non-indigenous species known to be established on the core sub-Antarctic islands (a figure itself likely to be a very conservative estimate of true numbers; Frenot *et al.* 2005) were introduced in this period rather than during the subsequent upsurge in research and tourism interest in the region since c. 1950 and 1980 respectively. However, Frenot *et al.* (2001) also document an increase in the rate of known introduction events after the establishment of research stations on the French sub-Antarctic islands in the 1950s and 1960s. Gressitt (1970) reports the presence of the majority of non-indigenous species known today on South Georgia in studies carried out during the 1960s.

Small-scale cultivation of vegetable crops for domestic use in "garden" areas and greenhouses has also been a feature of communities on various sub-Antarctic islands, and subsequently on several Antarctic research stations, most of which were established after the period under consideration. This activity is again closely associated with the introduction and establishment of non-indigenous invertebrate and plant species (Greenslade 1987, 2006, Frenot *et al.* 2005, 2008, Convey *et al.* 2006b; de Villiers & Cooper 2008). Deliberate historical introductions of trees are also known from some locations. For instance, vegetables and *Pinus pinaster* Alton were planted on Île Saint-Paul in 1857 but

TABLE 2

Vertebrate species introduced to southern ocean islands in association with the early decades of human occupation¹

Island	Vertebrate species accidentally or deliberately introduced (including those commensal with periods of human settlement but not established as feral populations)
Islas Diego Ramírez	‡ Sheep (some individuals, brought for fresh food supply) No other introduced vertebrates
South Shetland Islands	‡ Sledge Dogs — removed
South Orkney Islands	‡ Sledge Dogs — removed
South Sandwich Islands	Free of introduced vertebrates
Bouvet Island	Free of introduced vertebrates
South Georgia	Brown Rats (by 1820) — eradicated at certain sites Mice (1800s ?) Reindeer (1910-1925) † Rabbits (c. 1880 ?) — died out † Sheep — removed (Mutton Island) ‡ Cats, Dogs, Poultry, Horses, Pigs
Tristan da Cunha group	
Tristan da Cunha	Black Rats (1882), Cats (1810), Dogs (1820), Cattle (1820), Donkeys (1860), Geese , Goats , Mice (1700s), Pigs , Sheep (1820)
Nightingale	† Sheep
Inaccessible	† Cattle, Pigs, Sheep
Gough Island	Mice (by 1888), ‡ Cats (1919), Dogs (1919, 1957, 1962), Poultry (1956, 1971) ‡ Goats (1958-1959), Sheep (1956-1963)
Prince Edward Islands	
Marion Island	Mice (1900s) † Cats (1949) — eradicated in 1991 † Brown Trout <i>Salmo trutta</i> Linnaeus, 1758 — died out
Prince Edward Island	Free of introduced vertebrates
Archipel Crozet	
Île de La Possession	Black Rats (1850s?) Brown Trout <i>Salmo trutta</i> (1969, 1972) Brook Charr <i>Salvelinus fontinalis</i> Linnaeus, 1758 (1969) ‡ Sheep, Pigs, Poultry
Île de l'Est	Rabbits (after 1826)
Île aux Cochons	Mice (1800s?) Cats (by 1887) Rabbits (between 1837 and 1874) † Pigs (c. 1820) — died out
Îlots des Apôtres	Free of introduced vertebrates
Île des Pingouins	Free of introduced vertebrates
Îles Kerguelen	Black Rats (1900s) — eradicated on three small islands: Î. du Château in 2002, Î. Stoll in 2003, Î. Australia in 2004 Cats (present in 1900s, then extinct, reintroduced in 1951 and 1956) — unsuccessful control program by shooting in 1960 and in the 1970s, eradicated on Île Guillou in 1994 Mice (by 1874) Mouflon (1956, 1957) — only present on Île Haute in 2008, eradication planned in 2009 Rabbits (1874) — unsuccessful attempt at control using myxomatosis virus in the 1950s, successful eradication by poisoning on three small islands: Î. Verte in 1992, Î. Guillou in 1994, Î. aux Cochons 1997 Reindeer (1955-56) Sheep (1909-25, 1952) — only present on Île Longue in 2008 Brown Trout (1958, 1961, 1979) Brook Charr (1961) Arctic Charr <i>Salvelinus alpinus</i> (Linnaeus, 1758) (1990) Atlantic Salmon <i>Salmo salar</i> Linnaeus, 1758 (1975-1980) Coho Salmon <i>Onchorhynchus kisutch</i> Walbaum, 1792 (1978) † Rainbow trout <i>O. mykiss</i> (Walbaum, 1792) (1958) † Chinook Salmon <i>O. tshawytscha</i> Walbaum, 1792 (1955) † Lake Trout <i>Salvelinus namaycush</i> Walbaum, 1792 (1961) † Mink <i>Mustela vison</i> (Schreber, 1777) (1956) — died out † Pigs (feral, 1900s) ‡ Horses, Pigs (in pigsty), Poultry

Table 2 cont.

Island	Vertebrate species accidentally or deliberately introduced (including those commensal with periods of human settlement but not established as feral populations)
Île Amsterdam	Brown Rats (1931) Cats (1931) Cattle (1871) — partially removed in 1988, eradication planned Common Waxbill <i>Estrilda astrild</i> (Linnaeus, 1758) (1977) Mice (1823) † Goats (1823) — removed c. 1950 † Kerguelen Pintail <i>Anas eatoni eatoni</i> (Sharpe 1875)(1954) — removed c. 1970 † Pigs (1799) — removed c. 1873 † Sheep (1871) — removed c. 1954 ‡ Dogs, Pigs (in pigsty), Poultry
Île Saint-Paul	Mice (1800s?) † Black Rats (1700s?) — eradicated in 1997 † Rabbits (after 1874) — eradicated in 1997 † Cats (1877), Goats, Pigs
Heard Island and McDonald Island	Free of introduced vertebrates ‡ Atlas Cove Station: Dogs (1950), Sheep (1952, 1954)
Macquarie Island	Black Rats (1900s) Mice (1890s) Rabbits (1878) — control programme commencing in 1978, eradication planned Mallard <i>Anas platyrhynchos</i> Linnaeus, 1758 (arrived naturally, first record 1950s) Red Poll <i>Carduelis flammea</i> (Linnaeus, 1758) (arrived naturally, first record 1912) Starling <i>Sturnus vulgaris</i> Linnaeus, 1758 (arrived naturally, first record 1930) † Cats (by 1820) — eradicated in 2000 † Weka <i>Gallirallus australis scotti</i> (Ogilvie-Grant 1905) (1870s) — eradicated by 1989 ‡ Sheep, Goats, Poultry, Horses, Dogs
Auckland Islands group	
Auckland Island	Cats (1820s) Mice (1820s) Pigs (1807) † Goats (1840s) — eradicated in 1989–91 † Cattle (1850s), Horses (1850s), Dogs (1840s), Sheep (1840s)
Enderby Island	† Cattle (1849, 1894) — eradicated in 1991–1993 † Mice (1849) — eradicated in 1993 † Rabbits (1840) — eradicated in 1993 ‡ Goats (1865), Sheep (1849), Dogs (1842), Pigs (1842)
Rose Island	† Rabbits (1849) — eradicated in 1993 † Cattle (1894) and Sheep (1887)
Ocean Island	† Goats (1890s) and Sheep (1940s)
Adams Island	† Sheep and Goats (1890s)
Ewing Island	† Goats (1890)
Snares Islands	Free of introduced vertebrates
Campbell Island	† Brown Rats — eradicated in 2001 † Cats — eradicated in 2001 † Cattle (1931) — eradicated in 1984 † Sheep (1895) — eradicated in 1991
Antipodes Islands	Mice ‡ Cattle (establishment attempt failed)
Bounty Islands	Free of introduced vertebrates

In bold: species present in 2008.

In brackets: date(s) of introduction or first record.

† Died out or removed or eradicated.

‡ Present for a limited time in the past, usually associated with farming attempts or establishment of research stations, then died out or removed.

Scientific names for less frequent species are given in the table, otherwise see text.

¹ See also Taylor (1971), Davaine & Beall (1982), Headland (1984), Chapuis *et al.* (1994), McIntosh & Walton (2000), Chapuis *et al.* (2001), Copson & Whinam (2001), Fell (2002), Torr (2002), Jones *et al.* (2003c), Frenot *et al.* (2005), Taylor (2006), de Villiers & Cooper (2008), Terauds & Stewart (2008).

had disappeared by 1875 (Vélain 1877). More than 20 tree species were successfully planted on Île Amsterdam after the creation of its permanent research station in 1951 (Jolinon 1987, Frenot *et al.* 2001).

Inadvertent vertebrate introductions were also associated with many shipwrecks, in particular of rodents (House Mice, *Mus musculus* Linnaeus, 1758, Black Rats, *Rattus rattus* (Linnaeus, 1758), and Norway Rats (Brown Rats), *R. norvegicus* (Berkenhout, 1769)), a risk that occurs to the present day.

CONSEQUENCES

Infrastructure

The sealing, whaling and subsequent fishing industries exploited resources in the marine environment, causing drastic and possibly irreversible alterations to the Southern Ocean ecosystem (Trathan & Reid 2009). The infrastructure requirements of the former two industries on land and at the coast were in some cases considerable and, likewise, would have had drastic impacts on local terrestrial ecosystems. Taking the whaling industry on South Georgia as an example, at its height in the early twentieth century, seven shore-based stations operated in different bays on the more sheltered northeast coast of the island (fig. 1). Although three of these were closed down quite rapidly (Prince Olav Harbour, Ocean Harbour, Godthul), the remaining four larger stations operated until the 1960s, and three derelict and unmaintained stations remain today (Husvik, Stromness, Leith) with only

Grytviken having been partially preserved (pl. 1a–c).

These stations were built and operated before the development of today's climate of environmental awareness, and thus were not subject to baseline environmental data collection, environmental impact assessment or ongoing monitoring of impacts. However, they were clearly major industrial sites, occupying a large proportion of the available valley floor areas, and would inevitably have led to the complete destruction of large areas of the pre-existing terrestrial ecosystem within their coastal and valley locations, which would previously have provided the major contribution in terms of area of well-developed terrestrial ecosystems on the island. Construction and operation of the stations involved the import of all materials required for infrastructure, and would also have generated considerable levels of industrial pollution (pl. 1d), both from the station itself, and the large fleets of whale and seal catching vessels operating from them (indeed, some stations even had the capacity to construct and repair such vessels). After the stations were abandoned in the 1960s, with no cleanup or removal of hazardous material, they were essentially left derelict and at the mercy of the prevailing weather. Under pressure from the increasing tourism industry, the station at Grytviken was partially preserved and made safe for visitors in the early 2000s (see also McIntosh & Walton 2000), a process that served to highlight the quantities of hazardous material (e.g., asbestos, fuel oils, chemicals) still present on all the stations. At Grytviken, the assessment was made that, in the light of current international rules covering the transport of hazardous materials, some (in particular



FIG 1. — Map of South Georgia indicating the seven locations at which shore-based whaling stations were constructed in the early twentieth century.

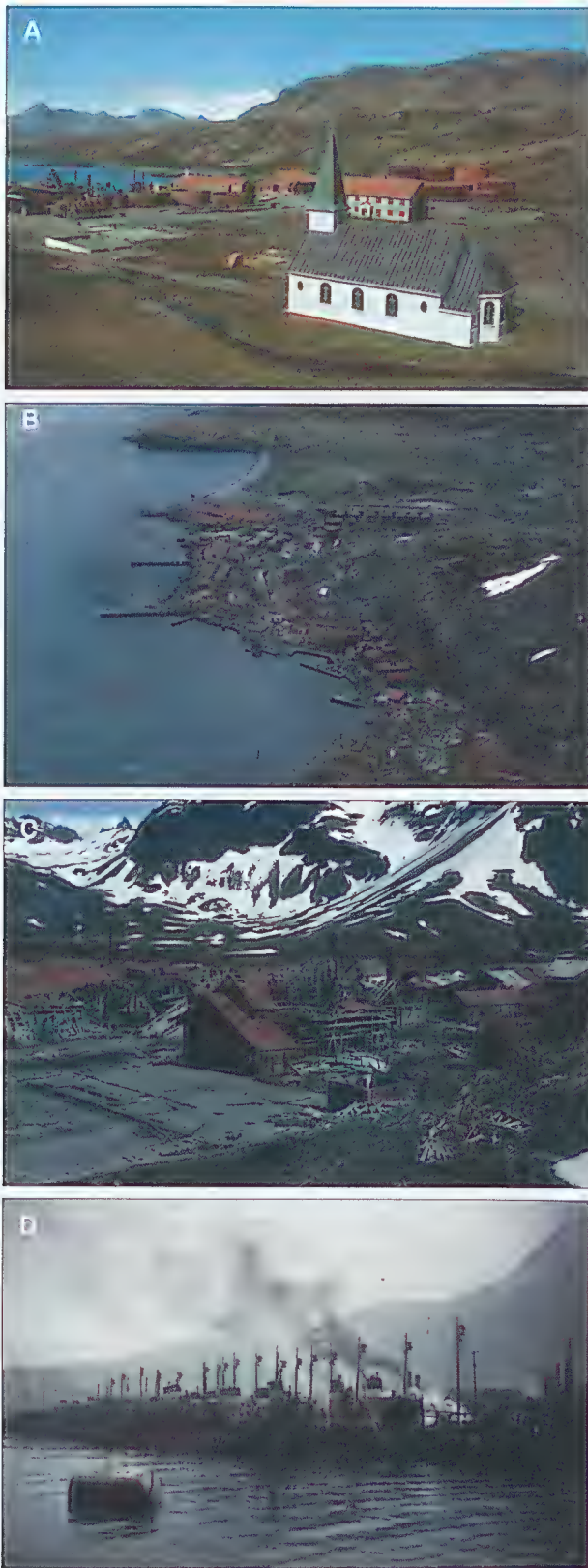


PLATE 1

South Georgia whaling stations: (A) view northeast over the recently partially-preserved Grytviken whaling station (Jan. 2006); (B) overview from north of the derelict Leith whaling station, illustrating the large proportion of the coastal low-lying ground directly impacted by its construction and operation (Dec. 1992); (C) derelict buildings and debris at Husvik whaling stations (Jan. 2006); (D) whaling vessels at a whaling station on South Georgia. (Photographs: A–C, P. Convey/BAS; D, N.A.G. Leppard, British Antarctic Survey Image Collection)

that contaminated with asbestos) had to be buried on site. The remaining three larger stations have not been subject to cleanup and preservation, and are currently classified as unsafe and closed to visitors by the Government of South Georgia and the South Sandwich Islands, although they are not secured and debris continues to be dispersed into the local environment, and both marine mammals, birds and introduced vertebrates (Reindeer, Brown Rats) regularly pass through and even establish breeding colonies within the stations.

Human presence inevitably involves requirements for movement and transport, and a network of paths and larger tracks quickly developed within, around and between sites of industrial exploitation and, subsequently, scientific research stations, research sites and field huts. Today, these track networks are known to have twin impacts in terms of being both conduits for the dispersal of non-indigenous plant species (with propagules carried on, for example, footwear and clothing) (Whinam *et al.* 2005, Frenot *et al.* 2008), and by their direct damage to vegetation and compaction of soil along their lines (Gremmen *et al.* 2003, Tejedo *et al.* 2009, Tin *et al.* 2009).

Transfer of marine biomass and nutrients to the land

The major harvesting industries of sealing and whaling would also have resulted in a considerable, but entirely unquantified, alteration of nutrient flows between the marine and terrestrial environments. The scale of harvesting involved was massive, including, for instance, the almost complete removal of the population of several million Antarctic Fur Seals, *Arctocephalus gazella* (Peters, 1875), from South Georgia, and the production of c. 100 000 barrels of oil from Southern Elephant Seals, on Heard Island. On South Georgia over 175 000 whales were processed between 1904 and 1966 (Hart 2006), with a further 85 000 being processed using factory ships and the shore station on Deception Island in the South Shetland Islands and Graham Land (northern Antarctic Peninsula, 1905–1931), c. 7000 in the South Orkney Islands (1911–1931) and c. 3000 in the South Sandwich Islands (1911/12 and 1927–1931) (Hart 2006). This level of harvesting resulted in the production of large quantities of unwanted carrion, which was simply dumped onshore or in the nearshore marine environment. The “waste” biomass associated with the onshore whale processing industry and factory ships located close to shore would probably have had the greatest impact locally, especially during the early years of the onshore processing industry when only the most valuable oil products were obtained — the density of whale bones on beaches of South Georgia bears witness to this. The transfer of marine biomass onto the land must have resulted in considerable fertilisation of coastal terrestrial habitats, while also providing a major food source for scavenging species of bird, and some native invertebrates, whose population dynamics would inevitably have been altered and that would also have distributed the nutrients more widely in the terrestrial environment.

The reduction in fur seal and Southern Elephant Seal numbers, and also penguins at locations where they were exploited for oil or as fuel for the processing of whale and seal oil, may have partially countered this effect on a local scale, through a reduction in manuring or guano input to terrestrial ecosystems. However, this reduction would also have resulted in much reduced levels of trampling of terrestrial habitats by these seals, which may paradoxically

have permitted expansion of the tussock grass and megaherb vegetation now regarded as typical of many sub-Antarctic islands into coastal regions in the vicinity of their breeding and haul-out locations. In the maritime Antarctic, recent expansions in Antarctic Fur Seal numbers and range (including to locations where they have not been present at least since Pleistocene glacial retreat) are documented to have resulted in considerable destruction of fragile terrestrial vegetation in the South Orkney and South Shetland islands (Smith 1988, Hodgson & Johnston 1997, Hodgson *et al.* 1998), a process now extending to locations along the Antarctic Peninsula. These expansions are thought to be directly linked with recovery of the source populations in the western part of South Georgia, which are at levels at least comparable with and possibly greater than those that existed pre-exploitation (Boyd 1993, Boyd *et al.* 1996). However, no comparable studies of their impacts on South Georgia (or other sub-Antarctic island) vegetation have been published, although populations of both Antarctic and sub-Antarctic (*Arctocephalus tropicalis* (J.E. Gray, 1872)) Fur Seals are recovering and subjective observation would indicate that maintenance of the “typical” vegetation is not compatible in the vicinity of the recovered Fur Seal populations (pl. 2).



PLATE 2

The impact of fur seal trampling on typical sub-Antarctic terrestrial vegetation — a comparison of (A) heavily impacted vegetation where tussock grass has been displaced and the dead tussock stools colonised by the moss *Polytrichum strictum* Brid. (Moltke Harbour, South Georgia) (Jan. 2006), and (B) non-impacted tussock grass vegetation from Cooper Bay, South Georgia (Jan. 2006) (photographs: P. Convey).

Impacts of introduced mammals and birds

The indigenous terrestrial faunas of the sub-Antarctic islands do not include mammalian herbivores or predators. Non-marine birds are limited on the core sub-Antarctic islands to a single (endemic to South Georgia) species of passerine, two ducks and two sheathbills. The New Zealand shelf islands host greater bird diversity. The anthropogenic introduction of vertebrate herbivores and predators to most sub-Antarctic islands has inevitably led to considerable deleterious impacts on indigenous ecosystems (Bonner 1984, Leader-Williams 1988, Chapuis *et al.* 1994, Bester *et al.* 2002, Frenot *et al.* 2005, 2008, Convey *et al.* 2006b), in some examples leading to the virtually complete destruction of native ecosystems (e.g., Chapuis *et al.* 1994, Bergstrom *et al.* 2009). On Île Amsterdam, grazing and trampling by feral cattle (introduced in 1871) and several fires, accidentally caused by human activity, have contributed to drastic ecosystem changes in low-altitude areas, including soil erosion, and dramatic decreases in native plant cover, most visibly that of the native tree *Phyllica arborea* Thouars (Frenot & Valleix 1990). According to early visitors, this tree formed a continuous belt along the east coast of Île Amsterdam, between 100 and 150 metres a.s.l. By 1874 only nine small patches of trees remained (Vélain 1877), and in 1988 most of the remnants were located in a single small wood. As part of a restoration program (Micol & Jouventin 1995) a fence was erected across the island in 1988, cattle were eradicated from the southern part, and 8000 individuals of *P. arborea* were subsequently planted (fig. 2). On Enderby Island and to a lesser extent on Rose Island the vegetation present in the 1950s (Taylor 1971) had been heavily modified by fire and introduced mammals, the latter subsequently being eradicated (Torr 2002).

In concert with the loss of native vegetation, grazing mammals have facilitated the spread of non-indigenous plant species, such as the grass *Poa annua* L., which in turn impacts the foraging dynamics of invertebrate communities (Chown & Block 1997). Several other plant species introduced in this era have now been identified as being “aggressive invasives”, capable of occupying new locations and displacing native species, and further “persistent invasive” species are predicted to change status as a consequence of contemporary climate change trends (Frenot *et al.* 2005). Introduced vertebrate predators (cats, rats, mice) have had drastic impacts on breeding bird populations on all islands to which they have been introduced, primarily through nest predation, leading to much reduced breeding diversity when adjacent islands with and without predators are compared (e.g., Anonymous 1996). A comparison between two similar islands, 20 km apart, in Archipel Crozet highlights the dramatic impact of rats on bird communities. Eight petrel species are present today on Île de la Possession, where rats were introduced in the nineteenth century, contrasting with 17 species on Île de l’Est which is free of rats (Jouventin *et al.* 1984). The size of the bird populations on adjacent small islands (around 150 ha) in the Golfe du Morbihan (Îles Kerguelen) has been estimated to be tens to hundreds of thousands of pairs in the absence of cats as against only 100 pairs in their presence (Chapuis *et al.* 2001). Rats and mice have wide-ranging impacts on vertebrate, invertebrate and vegetation elements of terrestrial ecosystems (e.g., Pye & Bonner 1980; Chown & Smith 1993, Le Roux *et al.* 2002, Jones *et al.* 2003a, Shaw *et al.* 2005, Phiri *et al.* 2009).

Non-indigenous invertebrates can also have important impacts on sub-Antarctic ecosystems. The predatory carabid beetles, *Trechisibus antarcticus* (Dejean, 1831) and *Merizodus soledadinus* (= *Ooapterus soledadinus*) (Guérin-Ménéville, 1832), are both spreading in their introduction areas on South Georgia (both species) and Îles Kerguelen (*M. soledadinus*), and having direct and indirect effects on their native and often endemic invertebrate prey species (Ernsting 1993, Ernsting *et al.* 1995, 1999, Chevrier *et al.* 1997, Frenot *et al.* 2008; see also Jones *et al.* 2003b). The spread of the non-indigenous flesh fly *Calliphora vicina* Robineau-Desvoidy, 1830 on Îles Kerguelen has been linked with reduced abundance of an indigenous dipteran competitor, *Anatalanta aptera* Eaton, 1875 (Chevrier *et al.* 1997). The detritivorous larvae of the introduced midge *Limnophyes minimus* Meigen, 1818 may contribute substantially to nutrient turnover on Marion Island, possibly comparable to that of the indigenous tineid moth *Pringleophaga marioni* Viette, 1968 (Hänel & Chown 1998). Slabber & Chown (2002) suggested that, if the introduced woodlouse *Porcellio scaber* Latreille, 1804 were to spread on Marion Island, it would substantially alter nutrient cycling by reducing the bottleneck currently imposed by lepidopteran larvae and earthworms. On Île Amsterdam phytophagous mammals do not form part of the native fauna and, in the absence of a typical coprophagous invertebrate fauna, the very numerous introduced woodlice play a major role in cattle dung degradation (Tréhen *et al.* 1990).

CONCLUDING DISCUSSION

It is clear from the foregoing that human activity has had considerable impacts on the terrestrial ecosystems of virtually all the sub-Antarctic islands. While primarily associated with the marine exploitation industries of sealing and whaling, the development and operation of industrial infrastructure and the transfer of large quantities of marine biomass and nutrients into the terrestrial environment will inevitably have had large but unquantified impacts on terrestrial ecosystems. The deliberate and accidental release of grazing and predatory vertebrates on most islands, as part of attempted farming operations or in support of shipwreck survivors, led to perhaps the greatest structural changes within these ecosystems and was accompanied by many inadvertent introductions of invertebrates and plants.

It is only in recent decades that the impacts of these various introductions on sub-Antarctic terrestrial ecosystem structure and function have started to be appreciated, and have become a serious cause for concern in the context of the conservation of these ecosystems and their biodiversity. Throughout the era between the islands' initial discovery and exploitation and the mid-twentieth century, ecological research and conservation were not issues of priority, and thus studies or documentation of human impacts, terrestrial ecosystems or non-indigenous species, or baseline biodiversity monitoring programs, simply do not exist. Thus, as illustrated by the discussion above relating to impacts of

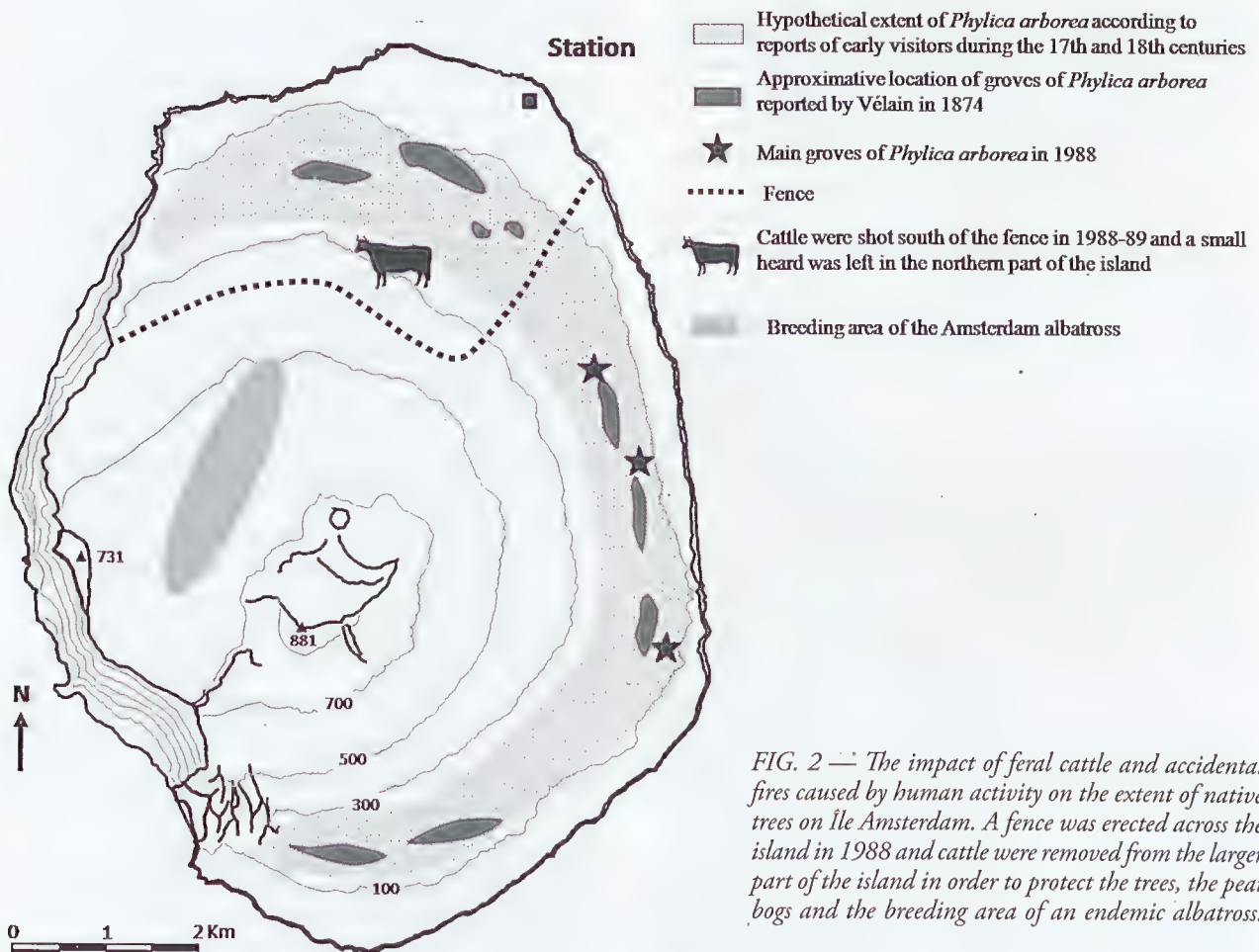


FIG. 2 — The impact of feral cattle and accidental fires caused by human activity on the extent of native trees on Île Amsterdam. A fence was erected across the island in 1988 and cattle were removed from the larger part of the island in order to protect the trees, the peat bogs and the breeding area of an endemic albatross.

fur seal exploitation and subsequent population recovery, some caution is required when attempting to identify the baseline (i.e., non-impacted) structure and distribution of sub-Antarctic terrestrial ecosystems — something that is an integral element of any attempt to identify potential consequences and indicators of contemporary environmental change. Conversely, there are also examples where the presence of non-indigenous species itself provides a valuable opportunity that would not otherwise be available to the research community. For instance, in certain archipelagos (e.g., Îles Kerguelen) the existence of reference and control islands (e.g. with or without introduced mammals) offers opportunities both to understand their direct impacts, and also to distinguish the effects of management intervention (e.g., eradication) from those of other factors (e.g., climate change) (Chapuis *et al.* 2002, 2004). Likewise, the impacts of introducing a new trophic function to an ecosystem (as with the example of predatory carabid beetles) can be explored by comparing adjacent impacted and non-impacted communities, providing an opportunity for field research to address fundamental questions of ecological theory.

Many of the impacts identified above as commencing during the era of human exploitation of sub-Antarctic resources continue to the present day. Thus, while some eradication programs have been completed (e.g., Chapuis *et al.* 2001, Bester *et al.* 2002), generally targeting specific introduced predators (cats, rats) as these are perceived to present the greatest threat at least to charismatic indigenous vertebrate populations, the consequences of these have not always been as straightforward or effective as hoped (see Courchamp *et al.* 2003, Chapuis *et al.* 2004, Frenot *et al.* 2005, Bergstrom *et al.* 2009). The large majority of non-indigenous vertebrates remain uncontrolled on most islands, with objective evidence now accumulating rapidly of their deleterious consequences for terrestrial ecosystems. No attempt has been made, or in most cases would be practicable, to eradicate any known non-indigenous invertebrates or plants introduced with human assistance (with some exceptions, e.g., *Sagina procumbens* (Linnaeus) on Gough Island (Gremmen *et al.* 2002), *Stellaria media* and *P. annua* on Snares Islands (Torr 2002)), while it is likely that many further examples remain to be recognised. Management plans and procedures developed for certain islands (e.g., Anonymous 1994, 1996, McIntosh & Walton 2000, Davies *et al.* 2007, Roberts 2007) now recognise the need to minimise the risk of new introduction events, and specify various measures to assist in achieving this end (see also Whinam 2009).

Exploitation of the resources of the Southern Ocean marine environment continues today in the form of various fisheries (fish, squid, krill, spider crabs) (Trathan & Reid 2009). Other than through seabird bycatch, one of whose associated impacts will be a reduction in transfer of marine-derived nutrients to the terrestrial environment. These do not involve the level of contact with the land as did the sealing and whaling industries. The primary risk is now that of shipwreck, as has occurred on several occasions in recent years, and particularly the risk of rodents thereby being introduced to areas that are currently rodent-free. Rather, the prime areas of interaction between humans and the sub-Antarctic terrestrial environment today take the forms of governmental scientific research activities and ecotourism. Together, these bring tens of thousands of individuals into the region each year, and considerable attention is now being given to identifying and minimising

the risks associated with these activities to the sub-Antarctic and Antarctic environments (Frenot *et al.* 2005, 2008, Convey 2008, Tin *et al.* 2009, Whinam 2009).

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ALIENS IN THE SUB-ANTARCTIC – BIOSECURITY AND CLIMATE CHANGE

by Jennie Whinam

(with four tables)

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Alien species constitute the biggest risk to the integrity of terrestrial sub-Antarctic ecosystems. The number of alien species is related to island size, temperature, human occupancy and visitation. Increasing numbers of tourists and expeditioners, combined with an amelioration in conditions associated with climate change are likely to result in an increasing number of alien species arriving at sub-Antarctic islands, as well as an increase in the distribution of existing alien species. Biosecurity is considered to be the most appropriate tool to minimise new introductions and establishment of alien species and to manage existing populations.

Key Words: sub-Antarctic, alien species, biosecurity, climate change.

INTRODUCTION

The aim of biosecurity in the sub-Antarctic is to minimise the risk of accidental introduction of alien species and diseases and to ensure rapid response to incursions if they occur. Different countries use varying degrees of biosecurity, supported by a variety of legislation and management plans.

Alien species are those that occur outside their normal or natural range, either as a direct or indirect result of human activity, or as self-introductions from a site of known human introduction (Parks and Wildlife Service 2006). The impact of alien species ranges from minor transient introductions to substantial loss of biodiversity and ecosystem changes. It is recognised that alien species pose the greatest threat to the integrity of natural ecosystems in the sub-Antarctic (Frenot *et al.* 2001). The threat of alien species establishing in the sub-Antarctic, as well as the likelihood of alien species present being able to expand their distribution, is considered likely to increase with the ameliorating conditions expected to occur with climate change on islands with depauperate floras and faunas and vacant niches (Bergstrom & Chown 1999, Chapuis *et al.* 2004, Frenot *et al.* 2005, Whinam *et al.* 2005). Some sub-Antarctic islands are already experiencing increases in air and sea-surface temperatures, with predictions that climate in the region will continue to change through the twenty-first century in line with twentieth-century trends (Pendlebury & Barnes-Keoghan 2007).

Island size, temperature, human occupancy and visitation have been identified as correlates of successful invasions on Southern Ocean islands (Chown *et al.* 1998). The most obvious impacts of alien species in the sub-Antarctic have been identified as: (i) extensive habitat modification or destruction by grazing vertebrates; (ii) local population reduction or extinction of indigenous bird species by alien predatory vertebrates; (iii) the introduction of new trophic levels (predators) into invertebrate communities where they were previously not present; and (iv) alterations in the levels of competition faced in plant and invertebrate communities (Convey *et al.* 2006). The type of impact varies with the alien species and the area that it is able to occupy, as well

as direct and indirect interactions between impacts.

Biosecurity is considered to be the most effective tool to prevent and manage alien species in the sub-Antarctic. Biosecurity is a pro-active concept, aligned with the pre-border, border and post-border continuum, a multilayered approach, with an emphasis on managing risk and border management (Biosecurity Australia, <http://www.daff.gov.au/ba>). Currently there is no unified approach to biosecurity across the sub-Antarctic, and therefore the aims of biosecurity vary slightly between the management authorities of different nations. The aims stated in the Heard Island Management Plan (Australian Antarctic Division 1995) outline the general intent of sub-Antarctic biosecurity – to ensure that no flora or fauna are introduced into the region as a result of human activity. The plan goes on to say that it is probably not possible to prevent microscopic organisms being introduced but concentrates on macroscopic species.

For biosecurity to be successful, it is necessary for a cultural change to occur, where biosecurity is regarded as a priority from the highest levels of management and legislation down to the people working in the sub-Antarctic and at the port facilities provisioning the islands. This may be relatively easy with tourists who are “one off” visitors to the area and with new expeditioners, but can take some time with long-term expeditioners, who may resist changes. For example, on Macquarie Island, a compromise was reached where the last two “pet” cats, *Felis catus* Linnaeus, 1758, were allowed to live out their lives in the early 1990s, but on condition that no further pets would be allowed.

Aliens across the sub-Antarctic

The number of alien species present varies dramatically across the sub-Antarctic and includes vascular plant species, vertebrates and invertebrates (table 1), microbial groups and diseases, and marine species. Some alien species pose little threat to the conservation of sub-Antarctic islands (e.g., *Anthriscus sylvestris* Hoffm. on South Georgia) while others greatly modify plant communities (e.g., mammal grazers, or plants reaching dominance in many different areas and

TABLE 1
Number of alien species of vascular plants, invertebrates and invertebrates on sub-Antarctic islands (from Convey 2008).

	South Georgia	Prince Edward Islands	Crozet archipelago	Kerguelen archipelago	Heard Island	Macquarie Island
Vascular plants	33	16	59	69	1	3
Invertebrates	12	19	14	30	3	28
Vertebrates	3	1	6	12	0	6

TABLE 2
Alien vertebrate species present on sub-Antarctic islands.¹

Species	South Georgia	Prince Edward Islands	Crozet archipelago	Kerguelen archipelago	Heard & MacDonald	Macquarie Island
Black Rat			1	1		1
Brown Rat	1					
House Mouse	1	1	1	1		1
Rabbit			2	1		1
Sheep				1		
Mouflon				1		
Reindeer	1			1		
Cat			1	1		
Salmonid fishes	0(1) ²	0(1)	2	8		
Mallard						1
Starling						1
Red polls						1
Total alien vertebrates	3	1	7	12	0	6

¹ From Frenot *et al.* 2005; Kerguelen fish data from Lésel *et al.* 1971 and Davaine & Beall 1997.
² The numbers in brackets are the number of alien species previously recorded from a sub-Antarctic island, with some numbers currently lower due to eradication or disappearance.

TABLE 3
Families of alien invertebrate species recorded from sub-Antarctic islands.¹

	South Georgia	Prince Edward Islands	Crozet archipelago	Kerguelen archipelago	Heard Island	Macquarie Island
Order						
Collembola	2	3	4	5	0	6
Blattodea	0	1	1	1	0	0
Psocoptera	0	0	0	1	0	0
Thysanoptera	0	0	0	0	1	0
Hemiptera	2	4	4	5	0	3
Coleoptera	2	0	0	2	0	0
Lepidoptera	0	1	0	0	0	0
Siponaptera	0	0	0	0	0	1
Diptera	5	6	2	7	0	1
Amphipoda	0	0	0	0	0	1
Isopoda	0	1	0	0	0	1
Acarina	0	0	0	2	1	10
Aranea	1	0	1	3	0	0
Phylum						
Annelida	0	1	2	3	1	4
Mollusca	0	1	0	1	0	1
Totals	12	18	14	30	3	28

¹ From Frenot *et al.* 2005, with additional information from H. Dartnall pers. comm.

habitats (e.g., *Taraxacum officinale* Wigg on Kerguelen). The alien species life forms that pose conservation and management problems for the sub-Antarctic vary between islands, although the Kerguelen Archipelago has the highest number of alien vascular plants, invertebrates and vertebrates. Some of the alien species on Kerguelen have been introduced as food sources, such as the Reindeer, *Rangifer tarandus* Smith, 1827, Mouflon, *Ovis orientalis orientalis* Gmelin, 1774, Sheep, *Ovis aries* Linnaeus, 1758, and trout and salmon, *Oncorhynchus* spp., *Salmo* spp. (table 2). The House Mouse, *Mus musculus* Linnaeus, 1758, is the most widespread alien vertebrate species, introduced to several sub-Antarctic islands and impacts upon invertebrates and plants (Convey *et al.* 2006).

Vertebrate pests (table 2) are generally identified as having the most environmental impacts in the sub-Antarctic, and are generally difficult and expensive to eradicate (Leader-Williams *et al.* 1989, Chapuis *et al.* 1994). For example, on some sub-Antarctic islands (e.g., the eastern part of the Kerguelen Archipelago and Macquarie Island), the combination of rabbit, *Oryctolagus cuniculus* (Linnaeus, 1758), impacts and recent climatic change is responsible for major changes in vegetation and some massive erosion (Copson & Whinam 1998, Chapuis *et al.* 2004, Scott & Kirkpatrick 2008). Vegetation cover is reduced by rabbit grazing and burrowing, while summer dryness significantly affects the vegetation which has developed largely in the absence of aridity. The resulting significant reduction in plant cover facilitates wind erosion, leading to long-term or irreversible degradation of ecosystems (Whinam *et al.* 2006, Courchamp *et al.* 2003).

Established vertebrate pests, such as cats, often have a complex interaction with native species on the island (Copson & Whinam 2001) and understanding their life cycle

and food sources is necessary for successful eradication. For example, multi-year programs using a variety of techniques were necessary to eradicate cats from Marion and Macquarie islands (Bester *et al.* 2002, Copson 2002). An ambitious Australian-Tasmanian government \$25 million, five-year program to eradicate rabbits, Black Rat, *Rattus rattus* (Linnaeus, 1758), and mice is currently being implemented for Macquarie Island (12 785 ha). This constitutes the second and third phases of an integrated vertebrate pest eradication program (Parks and Wildlife Service 2007) and follows on from the eradication of rabbits on three islands in the Kerguelen Archipelago in the early 2000s (Lebouvier & Frenot 2007) and the eradication of rats from Campbell Island (11 268 ha) in 2001.

Alien invertebrate species (table 3) are generally more difficult to detect, especially as there are limited baseline data available on most invertebrate groups in the sub-Antarctic (Greenslade 2006, Convey *et al.* 1999, Crafford *et al.* 1986). However, they can have severe impacts on sub-Antarctic ecosystems (Hänel & Chown 1998, Chown & Language 1994). This is illustrated by the invasion of the carnivorous carabid beetle, *Trechisibus antarcticus* Dejean, 1831, on South Georgia and the impact it has had on the endemic herbivorous beetle, *Hydromedion spassutum* (Ernsting *et al.* 1995). Marine introductions are difficult to detect and have only recently been recognised as a threat to the biodiversity of sub-Antarctic marine ecosystems (Lewis *et al.* 2003, 2006).

In terms of plant species, Poaceae is the most prominent family with alien species in the sub-Antarctic, with Asteraceae and Caryophyllaceae significant contributors (table 4). While alien Brassicaceae are only present on the Kerguelen and Crozet archipelagos, the risk that species from this family pose

TABLE 4
Families of alien vascular species recorded on sub-Antarctic islands
(from Frenot *et al.* 2005).

Family	South Georgia	Prince Edward Islands	Crozet archipelago	Kerguelen archipelago	Heard Island	Macquarie Island
Apiaceae	1	0	0	0	0	0
Asteraceae*	5	1	12	10	0	0
Boraginaceae	0	0	0	1	0	0
Brassicaceae	0	0	4	7	0	0
Campanulaceae	1	0	0	0	0	0
Caryophyllaceae	2	5	5	5	0	2
Chenopodiaceae	0	0	0	1	0	0
Ericaceae	2	0	2	0	0	0
Fabaceae	2	0	3	3	0	0
Hypericaceae	1	0	1	0	0	0
Onagraceae	0	0	1	1	0	0
Oxalidaceae	0	0	1	1	0	0
Plantaginaceae	0	1	1	1	0	0
Polygonaceae	1	1	3	3	0	0
Primulaceae	0	0	1	0	0	0
Ranunculaceae	2	0	1	1	0	0
Rubiaceae	0	0	4	0	0	0
Scrophulariaceae	0	0	1	0	0	0
Cyperaceae	2	0	0	0	0	0
Juncaceae	1	0	3	3	0	0
Poaceae	12	7	15	31	1	1
Woodsiaceae	1	0	1	1	0	0
Total	33	15	59	69	1	3

* Families that are most represented are highlighted in bold.

to the native flora of the region has been recognised, with fresh brassica vegetables banned from Macquarie and Heard islands, and recently from the French sub-Antarctic islands. This is primarily due to the threat that such Brassicaceae may pose to the megaherb *Pringlea antiscorbutica* Hook. f. and other native plant species through associated diseases and pests. Most of the higher plants established in the sub-Antarctic belong to common and widely distributed families that are often invasive at a global scale (Pysek 1998).

Alien species have been introduced to sub-Antarctic islands since humans explored the region, with the risk of introductions intensifying with increases in travel to the sub-Antarctic and between islands. There are data on the first record of alien plants for some sub-Antarctic islands, such as the French islands (Frenot *et al.* 2001) and for the Prince Edward Islands (Gremmen & Smith 1999). Some of the alien species present have been accidentally introduced during visits to the islands, while others have been intentionally introduced either as a food source (such as rabbits) or to be utilised (e.g., cats to control rodents or as pets). Some species are relatively recent incursions, such as *Anthoxanthum odoratum* L. on Macquarie Island, which was found beside a walking track in 1978 and removed in 1989 (Copson & Whinam 2001). Some species have re-appeared after either absence or eradication (Gremmen & Smith 1999). Other alien species, such as *Poa annua* L., are well established across the sub-Antarctic.

Vectors and risks

There is a link between alien species numbers and the number of human visitors over the past 200 years (Chown *et al.* 1998) and climate matching (Frenot *et al.* 2008). The sub-Antarctic has a long history of visitors commencing with whalers and sealers, and more recently, tourists and expeditioners. Currently, over 40 000 people travel to the Antarctic each year. Of the eight sub-Antarctic island groups, six are regularly visited by expeditioners and tourists (South Georgia, Prince Edward Islands, Crozet Islands, Kerguelen, Macquarie and Heard islands). There has been an increase in visits to the sub-Antarctic by tourists and independent adventurers in recent decades (International Association of Antarctic Tour Operators 2002). There is often much movement by Antarctic scientists and support staff within the area with many visiting other high-latitude or high-altitude areas in the year prior to travelling to the sub-Antarctic, which increases the risk of introducing propagules likely to successfully establish on the islands (Whinam *et al.* 2005). There is also the risk of transferring biota indigenous to one part of the sub-Antarctic to another, especially as these species are already adapted to the environmental conditions (Convey 2008).

A risk assessment of cargo, food and expeditioners in transit to the sub-Antarctic found that cargo containers, clothing, machinery, boats and some cargo goods posed a high risk as vectors for introducing alien species (Whinam *et al.* 2005). Equipment identified as high-risk vectors included equipment cases, day packs and the cuffs and Velcro R closures of outer clothing (Whinam *et al.* 2005).

Aliens in Antarctica program

Aliens in Antarctica is an international program involving eight countries endorsed by the Scientific Committee on Antarctic Research (SCAR) as part of the 2007/08 International Polar Year (IPY). It is a component of SCAR's

Evolution and Biodiversity in the Antarctic Science Program (EBA). This project follows on from previous work indicating that people are vectors in inadvertently transporting alien species into the Antarctic region (Lee & Chown 2009, Whinam *et al.* 2005, Gaston *et al.* 2003).

The Aliens in Antarctica program assessed the propagule load carried by people on over 40 Antarctic voyages and/or flights into the Antarctic and sub-Antarctic islands during the 2007/08 summer (http://www.ipy.org/index.php?ipy/detail/aliens_in_antarctica/). Expeditioners' outer clothing and equipment was inspected for propagules. Samples were collected and identified to the lowest taxonomic level possible and using scaling-up procedures total propagule loads will be assessed. Seeds from over 300 taxa have been collected with boots, backpacks and camera bags appearing to be the main items carrying propagules. National personnel were in general carrying more seeds than tourist or ship crew (IPY Aliens in Antarctica unpublished data – D.M. Begstrom pers. comm.).

Recent travel histories of expeditioners were also recorded, to assess potential sources of propagules. The significance of this element of the project is that propagules from cold areas such as the Arctic will have a greater chance of establishing in the Antarctic than those from warmer ecosystems.

While various countries are at different stages of adopting biosecurity strategies, the risks, vectors and possible management strategies are similar across the sub-Antarctic. It will be necessary for international collaboration to minimise the risk of further introductions from home ports to the sub-Antarctic, as well as accidental island-to-island arrivals. The results of work to date indicate that the most effective way to minimise introductions will be to have uniform policies where possible and to treat the biosecurity risks posed by tourists, expeditioners and adventurers equally.

There has been significant progress in some countries, as data highlighting high-risk areas has become available. For example, the French sub-Antarctic islands were granted the status of Nature Reserve in 2006, which gives the islands greater protection for the environment and biota, with management plans expected to be in place by 2010 (Lebouvier & Frenot 2007). Some management actions relating to biosecurity have already been initiated. The French management authorities, Terres Australes et Antarctiques Françaises (TAAF) with the French Polar Institute (IPEV) have ceased transporting fresh cabbages to the sub-Antarctic after these were found to carry a high number of invertebrates (Lebouvier & Whinam unpubl. data). In addition, the French are dismantling glasshouses on Îles Amsterdam and Crozet, after a high number of alien invertebrates and plant species were recorded (Lebouvier & Whinam unpubl. data). The number of vegetable and flower gardens on Île Amsterdam are also being reduced. These have been rapid adaptive management changes in response to data recently collected.

Threats to native species

The threat that disease poses to Antarctic wildlife has been recognised at an Antarctic Treaty Consultative Meeting, which led to a "Workshop on Diseases of Antarctic Wildlife" in 1998. The workshop recognised that there was a significant risk of the introduction of disease into Antarctic wildlife species and that should it occur the consequences are likely to be serious and a response will be required (Kerry *et al.* 1999).

Examples included serological evidence for exposure of

Adélie, *Pygoscelis adeliae* (Hombron & Jacquinot, 1841), and Emperor penguins, *Aptenodytes forsteri* Gray, 1844, at some locations near Mawson to Infectious Bursal Disease Virus (IBDV). This virus causes serious disease in poultry. The presence of viruses and diseases highlights the increasing risk of disease being introduced into the fauna because of the increase in the numbers of people travelling to and within Antarctica (Kerry *et al.* 1999).

The milder climate associated with sub-Antarctic islands means that arthropod vectors of infectious disease such as ticks and fleas are likely to be present and are able to complete their life cycle. It is possible therefore that disease may be introduced into the wildlife of these islands more readily than to Antarctica if ticks and fleas carrying the disease are accidentally introduced and that they in turn may also play a role in the transmission of disease into Antarctic wildlife (Kerry *et al.* 1999).

Human activity in the sub-Antarctic could be the cause of disease outbreaks by a number of direct and indirect mechanisms. People could act as vectors for infectious agents, either by bringing non-indigenous pathogens into the region or by translocating indigenous pathogens (Frenot *et al.* 2008). Avian Paramyxoviruses (APMV) and antibodies to Newcastle Disease (NDV) have been reported from Macquarie Island Royal Penguins, *Eudyptes schlegeli* (Finch, 1876) (Morgan & Westbury 1981). In addition, stress caused by human activity could reduce immunity, increase pathogenicity and could cause the expression of a disease that might otherwise not have revealed itself (Kerry *et al.* 1999). However, humans are not the only mechanism for disease incursion to the sub-Antarctic. New diseases could be carried to the continent by migratory species and by atmospheric events.

An example of species affected by disease includes the two species of albatross breeding on Île Amsterdam. The Amsterdam Albatross *Diomedea amsterdamensis*, Roux, Jouventin, Mougins, Stahl & Weimerskirch, 1983, is listed as critically endangered, and the Indian Yellow-nosed Albatross, *Thalassarche carteri* (Mathews, 1912) listed as vulnerable. A combination of factors is thought to have contributed to their decline, including degradation of habitat due to cattle, *Bos taurus* Linnaeus, 1758 predation by feral cats, longline fishing and susceptibility to diseases such as Avian Cholera (*Pasturella multocida*) and *Erysipelothrix rhusiopathidae* (Weimerskirch 2004, Birdlife International 2009).

Climate change, a new challenge for biosecurity

Both the direct and indirect impacts of climate change are likely to influence the number of alien species present in the sub-Antarctic and their impacts. Glacial retreat is an indicator of climate change (Pendlebury & Barnes-Keoghan 2007) and offers the prospect of large areas of relatively fertile, newly disturbed ground being available for colonisation by both native and alien species. Many alien species that are becoming widespread in the sub-Antarctic, such as *Poa annua*, have characteristics that can give them an advantage in establishing in these conditions.

Propagules of plant species that have previously arrived in the sub-Antarctic are more likely to be able to germinate and colonise in the changing and ongoing predicted ameliorating conditions (Pendlebury & Barnes-Keoghan 2007). In the Austral summer of 2004/05, we observed *Poa annua* colonising newly available ground immediately in

front of the retreating Glacier Ampère at La Mortadelle, Îles Kerguelen (see also Frenot *et al.* 1998). Similarly, *P. annua* has colonised previously glaciated ground near Winston Lagoon on the south coast of Heard Island (Scott 1989).

Another likely result of a more favourable climate is that alien species that currently exist on sub-Antarctic islands are likely to be able to expand their presence. An example of this is *Taraxacum officinale* on Îles Kerguelen. This species previously occurred in small numbers on the coastal slopes on Île Australia, downwind of Île Longue, where sheep are grazed. By the time of our visit in 2004/05, this weedy daisy was the dominant flower on the coastal slopes on Île Australia and was present further inland. *Rumex acetosella* L. was present in small numbers around the main station on Marion Island for many years. However, with a more favourable climate it has now spread further along the island and is altering the ecosystems of some peatlands and wetlands (S.L. Chown pers. comm.). *Poa annua* has expanded its range (Scott & Kirkpatrick 2005) northwards on Heard Island to land deglaciated by the retreat of the Stephenson Glacier (Kiernan & McConnell 2002).

It is acknowledged that new diseases, weeds and pests are likely to be able to colonise sub-Antarctic islands in ameliorating weather conditions (Frenot *et al.* 2005, Bergstrom & Chown 1999, Chown & Language 1994). For example, the introduced fungus *Albugo candida* Kuntze probably transferred from fresh vegetables to infecting stands of Kerguelen Cabbage (*Pringlea antiscorbutica* Hook. f.) on Îles Kerguelen (Frenot *et al.* 2008). We do not know which species or diseases are likely to appear, and so the only real management option is to have stringent biosecurity measures in place to minimise the risk of these arriving, be able to identify them shortly after arrival if this does happen, and be able to take the necessary management actions, such as eradication, native species protection or control. Baseline knowledge is essential to evaluate and monitor the impacts of alien species on sub-Antarctic environments (Walton & Shears 1994), especially in relation to identifying appropriate management responses and assessing the efficacy of restoration programs.

In addition to the problems that managing alien species and diseases pose in the face of climate change, there are also likely to be changes in the balance of native species. For example, a combination of apparently drier conditions on Macquarie Island combined with a massive number of rabbits, estimated to be more than 100 000 (Parks and Wildlife Service 2008), has led to the less palatable *Acaena magellanica* Lam. becoming dominant over large areas. A similar situation has been observed on Grande Terre (Kerguelen), where *A. magellanica* now forms “nearly monospecific heathlands” (Lebouvier & Frenot 2007, p. 25). The density of the cover will make it difficult for other native, more palatable species to re-establish when rabbit numbers are reduced.

There is also the likelihood that species will be able to “move” to occupy other habitats as climate conditions ameliorate and/or as barriers disappear. For example, as the glaciers retreat on South Georgia, Reindeer have been able to move to new areas which were previously free of these grazers, and of their environmental impacts (Moen & MacAlister 1994). The *Sphagnum* mires of high conservation value in the high-altitude calderas on Île Amsterdam are currently relatively free of weed species (Whinam & Lebouvier unpubl. data). However, there is a number of alien plant species that occur at lower altitudes on the island that are

likely to be able to colonise these higher altitude sites in future, if conditions become suitable for an altitudinal shift.

Biosecurity and the future

It is clear, that for the sub-Antarctic to be protected from the accidental introduction of alien species, the management authorities in all countries involved will have to plan for the unexpected. Despite precautions, there are likely to be many more unforeseen disease, weed and invertebrate incursions with increasing numbers of visitors and biosecurity management must be robust to prevent their arrival. There is a need to identify their presence and take management actions to remove or manage their presence. In addition to increased visitor numbers, the direct and indirect impacts of climate change have implications for the management of biosecurity. Management plans for sub-Antarctic islands, such as for Prince Edward and Macquarie islands (DEAT 1996, Parks & Wildlife Service 2006), highlight the importance of biosecurity in the light of climate change predictions.

Biosecurity will need to be afforded greater priority in sub-Antarctic management – resources will be required for ensuring alien species do not depart ports/airports, that rigorous checking occurs en route to the sub-Antarctic, that there is appropriate expertise available to identify arrival of alien species and that management responses exist. If incursions do occur, then rapid and effective response will be essential, especially as climate conditions become more conducive to new alien species establishing and expanding in the sub-Antarctic. For example, in December 2008, widespread dieback of the Macquarie Island endemic cushion plant, *Azorella macquariensis* Orchard, was reported (Bergstrom unpubl. data). The dieback has spread rapidly and, by June 2009, surveys by Parks and Wildlife Service rangers showed that dieback was present over all of Macquarie Island, including areas that are rarely visited. Samples collected have been analysed and have not shown evidence of pathogens. However, root material needs to be collected during the next shipping season for pathogenic analysis. Some seed was collected in March 2009 and it is planned to collect fresh material for tissue culture during the next shipping season. Obviously, identification of causal factors for this widespread dieback is necessary for an effective management response. In the meantime, biosecurity precautions have been instigated on personnel travelling on Macquarie Island, as well as expeditioners and equipment exiting the island.

The approach to sub-Antarctic biosecurity has been piecemeal to date, decided and managed by individual nations. The movement of tourists and expeditioners between sub-Antarctic islands and Antarctica indicates that this should change to a co-ordinated international approach. The international collaboration that at present exists in relation to sub-Antarctic biosecurity will have to be strengthened – possibly through an international agreement similar to the Antarctic Treaty – to ensure appropriate biosecurity across the region, targeting tourists, adventurers, expeditioners and cargo.

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EXPANDED ABSTRACT

MANAGING INVASIVE ANIMALS ON SUB-ANTARCTIC ISLANDS

by K. G. Broome

Broome, K.G. 2009 (11:xii) Managing invasive animals on sub-Antarctic islands. *Papers and Proceedings of the Royal Society of Tasmania* 143(1): 53–55. ISSN 0080-4703. Department of Conservation, PO Box 516, Hamilton 3240, New Zealand. Email: kbroome@doc.govt.nz

People have deliberately or accidentally introduced animals to many sub-Antarctic islands over the past 250 years. Environmental changes as a consequence of these introductions can be inferred from observations made directly before or following eradication. Broad options for managing invasive animals include prevention, eradication, sustained control or no control, circumstances usually dictating the best option. Examples of successful management of invasive animals in the sub-Antarctic region include Enderby and Campbell islands. Key challenges in furthering management of invasive animals in the region include improving biosecurity to prevent pests reaching new locations (including islands from which they may have been eradicated) and increasing the scale of islands on which eradication of rodents is attempted. Success with the Macquarie Island rabbit eradication project will greatly increase understanding and confidence in what can be done.

Key Words: sub-Antarctic islands, human impacts, invasive alien species, conservation, management, eradication.

INTRODUCTION

Island habitats represent only three per cent of the Earth's land area but island species make up 64% of the world's known extinctions and 45% of endangered species are known to occur on islands. This paper provides an overview of invasive animals in the sub-Antarctic to give context to a project currently underway to eradicate European Rabbits *Oryctolagus cuniculus* (Linnaeus, 1758) and rodents from Macquarie Island (12 800 ha). Management of other invasive species in the region such as plants and pathogens, whilst important, is not considered.

HISTORY

The sub-Antarctic region is mostly ocean, making terrestrial habitats both scarce and important for many species of wildlife including marine species which come ashore to breed. Humans have deliberately or accidentally introduced animals to many of these islands over the past 250 years (Convey 2007, King 2005, Torr 2002, Atkinson 1985). Deliberate releases in the eighteenth and nineteenth centuries were intended to provide a ready source of wild food for sealers and shipwrecked sailors. Attempts at farming on some islands met with mixed success and led to abandoned or feral herds (Fraser 1986). Rodents commonly reached islands accidentally, carried in equipment or stores (Atkinson 1985, Taylor 2006). A few birds, such as the European Starling, *Sturnus vulgaris* Linnaeus, 1758, arrived unassisted as a consequence of their deliberate introduction to inhabited countries further north.

Only a small number of islands remain free of pest animals in the sub-Antarctic region, mainly due to a combination of chance and their relative lack of human activity. Although successful eradication projects have removed pest animals from a few islands, at least one species of invasive animal occurs on the majority of islands in the region (Convey 2007, Atkinson 1985, Smith 2007).

IMPACTS

We can infer the environmental changes attributable to invasive animals in the region from differences between similar islands with and without particular species or from observations of the successful reintroduction or recolonisation of extirpated native species following eradication of pests. The endemic flightless Campbell Island Teal, *Anas aucklandica nesiotis* (Fleming, 1935), provides an example of the latter. Not seen in living memory on Campbell Island, ornithologists rediscovered it on nearby Dent Island (23 ha) in 1975 (Williams & Robertson 1996). Reintroductions of captive-bred teal following the successful eradication of Norway Rats (Brown Rats), *Rattus norvegicus* (Berkenhout, 1769), from Campbell Island in 2001 have led to a viable breeding population requiring no further management.

Introduced House Mice, *Mus musculus* Linnaeus, 1758, studied on Gough Island were observed attacking Tristan Albatross, *Diomedea dabenena* Brooke, 2004, chicks on their nests, causing massive wounds and leading to the death of about half the chicks produced (Angel *et al.* 2006).

The impacts of herbivorous animals can be inferred by using fenced plots which exclude the pest from the vegetation. Changes in flora within the fence are compared with those outside where access to grazing remains. Examples occur on Macquarie Island where vegetation recovery following the removal of rabbit grazing is apparent (Carmichael 2009).

OPTIONS FOR MANAGEMENT

There are four broad options for managing invasive animals in the sub-Antarctic region:

- Prevention – Preventing further spread of invasive species is the most cost-effective option for all sub-Antarctic islands. Taking steps to prevent further invasions should be the highest pest management priority even where islands already have some animal pests established.
- Eradication – Totally removing the pest population, where feasible, offers a permanent solution provided reinvasion (see option 1) and undesirable consequences of eradication are managed.

- Sustained control – Ongoing population control is a complex option to manage the impacts of introduced species in perpetuity, either through chemical, physical or biological means. The benefits dissipate if control stops, so sustaining the effort is important and can be difficult in terms of technology, logistics and politics.
- No control – A choice to do nothing could be justified in three ways: first, if the benefits of management action do not outweigh the costs; second, a lack of capability to undertake the work; and third, a lack of priority for available resources. Typically managers invest in research which may investigate potential benefits and costs or to build the knowledge and capability to address the problem or support the justification for priority. Nevertheless, until management action is taken, research effort remains technically within the “no control” option.

There are six components to successful invasive species management (Broome & Fairweather 2008):

- An understanding of the problem and how each pest species contributes to this, e.g., recruitment failure through egg predation by Black Rats, *Rattus rattus* (Linnaeus, 1758), versus mortality of fledglings by Brown Skua, *Stercorarius antarcticus* (Lesson, 1831), as a result of burrow entrances exposed through rabbit grazing.
- A strategy which clearly articulates goals and priorities.
- Technology and equipment which does the job effectively and efficiently.
- Skills and experience to carry out the required tasks competently.
- Funding.
- Community acceptance of the strategy, funding and technology being used.

EXAMPLES OF PEST MANAGEMENT IN THE SUB-ANTARCTIC REGION

Enderby Island in the Auckland group had cattle introduced in a failed attempt at farming and rabbits introduced as castaway food for shipwrecked sailors. Mice probably arrived in the mid-nineteenth century. The cattle were eradicated in the early 1990s. In 1993 a helicopter was used to spread poison bait for rabbits and mice. A hunting team followed up immediately afterwards to remove the last surviving rabbits (Torr 2002). Enderby Island is now free of introduced mammals.

In 2001, Department of Conservation staff targeted Norway Rats on Campbell Island with aerially-applied poison baits, this time using Global Positioning System (GPS) navigational guidance to fly parallel flight lines across the island. At 11 300 ha Campbell Island had a far bigger area than previous eradication programs had attempted, but careful planning and dedicated personnel resulted in successful eradication (McClelland & Tyree 2002).

Tasmanian Parks and Wildlife Service staff successfully eradicated Weka, *Gallirallus australis scotti* (Ogilvie-Grant, 1905), and Feral Cats, *Felis catus* Linnaeus, 1758, from Macquarie Island. The work currently underway on this island targets the final three animal pests (mice, Black Rats and rabbits) in a single project involving aerial poison baiting and follow-up hunting of surviving rabbits (Parks & Wildlife Service 2007). The scale of Macquarie Island (12 800 ha) looks challenging compared with previous attempts for mice and rabbits. Campbell Island is similar in size but the operation was comparatively simple in targeting a single pest

species. However, Campbell Island managers faced similar issues in 2001: a lack of comparable precedents alone does not determine feasibility.

FUTURE OPPORTUNITIES AND CHALLENGES

Opportunities exist throughout the region for further management work on invasive animals. Continued sharing of expertise and lessons gained from each project will give the greatest chance of success. Priority setting should consider opportunities to consolidate the management of biosecurity, by reducing the potential for animals to be spread from one island to another within the region, as well as to provide further pest-free environments for the flora and fauna that inhabit this region.

Invasive animal management in the region faces two key challenges. The first is to address the issue of biosecurity to stop pests moving to new islands or islands from which they have been eradicated. Finding innovative solutions to effective quarantine management, efficient surveillance systems to provide early warning, and reliable capacity to respond to incursions on such remote and logistically difficult islands is the challenge to be overcome. Island quarantine can be regarded as a social problem as it is within the control of humans visiting islands to minimise the risks given the right information, motivation and ability to act. Management agencies should lead by example and work to create an environment of shared values, understanding of risk and willingness to constantly improve.

The second major challenge is developing the technology to make another leap of scale in the size of islands on which the eradication of rodents is attempted. The Macquarie Island project will test the limits of scale using existing techniques.

However, far larger islands in the region could benefit from rodent eradication, if the attempt can be made logistically feasible and affordable. For example, the eradication of mice from the 50 000 ha Auckland Island using current techniques would require 800 tonnes of poison bait applied to the island. The logistics of such an exercise become overwhelming in such a challenging environment.

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PAPERS AND PROCEEDINGS OF THE ROYAL SOCIETY OF TASMANIA
VOLUME 143, PART 2

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BIOLOGY AND POPULATION STUDIES OF TWO ENDEMIC *NEMATOCERAS* (ORCHID) SPECIES ON SUB-ANTARCTIC MACQUARIE ISLAND

by M. L. Skotnicki, G. R. Copson, J. Doube, L. Gadd, J. M. Selkirk-Bell
and P. M. Selkirk

(with one text-figure, three plates and one table)

Skotnicki, M.L., Copson, G.R., Doube, J., Gadd, L., Selkirk-Bell, J.M. & Selkirk, P.M. 2009 (11:xii): Biology and population studies of two endemic *Nematoceras* (orchid) species on sub-Antarctic Macquarie Island. *Papers and Proceedings of the Royal Society of Tasmania* 143(2): 61–71. ISSN 0080-4703. Functional Ecology Group, Research School of Biology, Australian National University, Canberra, ACT 2601, Australia (MLS*); Dept of Primary Industries, Parks, Water and Environment, GPO Box 44, Hobart, Tasmania 7001, Australia (GRC); Australian Antarctic Division, Channel Highway, Kingston, Tasmania 7005, Australia (JD); Tasmanian Parks and Wildlife Service, PO Box 126, Moonah, Tasmania 7009, Australia (LG); 85 Lawson Street, Spring Gully, Victoria 3550, Australia (JMS-B); Department of Biological Sciences, Macquarie University, Sydney, NSW 2109, Australia (PMS)
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Two endemic orchid species, *Nematoceras dienenum* and *N. sulcatum*, are known from sub-Antarctic Macquarie Island. Several additional orchid populations on the island are reported and cleistogamy is documented in *N. dienenum* for the first time. The known population sizes, habitats and locations for both orchid species are documented here, and new information on their biology and population ecology is provided.

Key Words: *Nematoceras*, *Corybas*, helmet orchid, Macquarie Island, sub-Antarctic.

INTRODUCTION

Two endemic species of orchids, *Nematoceras dienenum* (D.L. Jones) D.L. Jones, M.A. Clem. et Molloy (Brown *et al.* 1978, Jones 1993) and *N. sulcatum* M.A. Clem. et D.L. Jones (Mackenzie *et al.* 2005, Clements & Jones 2006, Clements *et al.* 2007) are known from the northern half of sub-Antarctic Macquarie Island (fig. 1). Members of the genera *Nematoceras* and *Corybas* are amongst those referred to in Australia as “helmet orchids” but referred to in New Zealand as “spider orchids”. The two Macquarie Island species have recently become known by the common names Windswept Helmet Orchid (*N. dienenum*) (Wapstra *et al.* 2005) and Grooved Helmet Orchid (*N. sulcatum*) (Wapstra *et al.* 2007).

Since the discovery of *N. dienenum* in 1976 as *Corybas macranthus* (Brown *et al.* 1978), morphological, taxonomic and systematic studies have been made (Mackenzie *et al.* 2005, Clements & Jones 2006, Clements *et al.* 2007), but the orchid populations, like many plant populations on Macquarie Island, have been poorly studied. Here we document population sizes, habitats and locations for these unique sub-Antarctic orchids, and provide new illustrations and information on their life histories and population ecology.

Approximately halfway between Tasmania and Antarctica, Macquarie Island has an area of 12 785 ha (Parks and Wildlife Service 2006) (fig. 1). It is uplifted ocean floor that first emerged above sea level 600 000–700 000 years ago (Adamson *et al.* 1996), is the above-sea portion of the Macquarie Ridge, and has never been connected to any other land mass. All indigenous terrestrial and freshwater

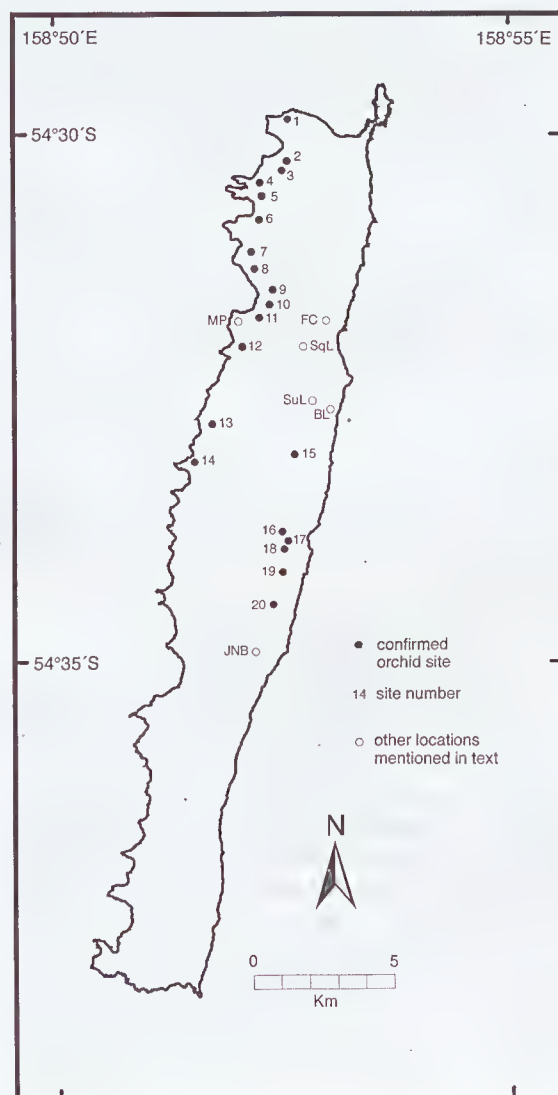


FIG. 1 — Map of Macquarie Island showing known *Nematoceras* populations at sites numbered as in table 1. Other locations mentioned in text are shown by initials: MP Mawson Point, FC Finch Creek valley, SqL Square Lake, BL Brothers Lake, SuL Surrey Lake, JNB Jessie Niccol Basin.

organisms have reached the island by long-distance transoceanic dispersal via ocean currents, winds or birds (Brown *et al.* 1978, Bergstrom & Selkirk 1987, Muñoz *et al.* 2004, Dartnall *et al.* 2005).

The genus *Nematoceras* Hook.f. is endemic to New Zealand and Southern Ocean islands (Clements *et al.* 2007). To the south of New Zealand, one species occurs on Antipodes Island (49°41'S, 178°48'E) and two species on the Auckland Islands (50°29' to 50°59'S, 165°52' to 166°20'E). The flora of Campbell Island (52°33'S, 169°09'E), includes eight species of orchid, including two species of *Nematoceras* (NZ Native Orchid Group 2009). The two species of *Nematoceras* endemic to Macquarie Island (vicinity of 54°30'S, 158°55'E) are the most southerly in the genus. Although five species of orchids are known from further south, in Tierra del Fuego, South America (Moore 1983), the two species of *Nematoceras* endemic to Macquarie Island are of great interest, being the only orchids known from an oceanic sub-Antarctic island.

MATERIALS AND METHODS

Field studies were undertaken on Macquarie Island between 1977 and 2009. During field surveys in 1978 and 1980–81 for the *Flora Atlas*, orchids were recorded as “local and rare” in 14 of the island’s 1 km² grid squares (Copson 1984). Because of the vagaries of shipping access to Macquarie Island, many visits by summer scientists (MLS, JMS-B, PMS) were of limited duration or at suboptimum times of year for assessing orchid growth. Overwintering personnel (GRC, JD, LG) have been able, alongside their other tasks on the island, to extend observations into the autumn, winter and spring months.

During summer 2004 and 2009, as many of the known populations of orchids were visited as time allowed. Their extent and precise locations were recorded using hand-held Global Positioning Systems (GPS). During 2006 and 2007, thorough searches for further orchid populations were made, concentrating on locations with habitats apparently suitable for orchid growth such as very moist areas with low-growing vegetation similar to sites where orchid populations had been found. The stage of flower development was documented for each population whenever possible.

Voucher specimens for the two orchid species from Macquarie Island are lodged in the Australian National Herbarium, Canberra (CANB) and the Tasmanian Herbarium, Hobart (HO).

RESULTS

Location of populations

In summer 2004 and subsequently, GPS were used to record the extent and precise locations of known populations of orchids (fig. 1, table 1). Locations where orchids had earlier been recorded, but which could not be accessed during summers 2004–09, are also included in table 1. During 2006, 2007 and 2009, the extent and precise location of several new populations were recorded at Bauer Bay, in the Green Gorge North basin and the Red River valley (table 1). Flower development in several populations was recorded and photographed over the summer months.

Searches between late spring and early autumn failed to find further orchid populations in other parts of the island

with apparently suitable habitats, including the Jessie Niccol Basin, the Sawyer Creek valley, the western and eastern edges of Red River valley, Finch Creek valley, the environs of Square Lake, the drainage line into Brothers Lake from the south, the drainage line towards Brothers Hut from the south, and the basin below Surrey Lake (fig. 1).

Populations of *N. dienemum*

The largest known population of *N. dienemum* occurs at Handspike Corner where a few plants are scattered over an area of roughly 100 m x 100 m (fig. 1, table 1). Most plants are clustered in slightly sheltered and very wet locations in hollows in the ground, many around pool margins, between the rocky shoreline and about halfway to the base of the escarpment. Recent overgrazing by European Rabbits, *Oryctolagus cuniculus* (Linnaeus, 1758), on the island has completely removed the shelter previously provided by leaves of *Stilbocarpa polaris* (Homb. et Jacq.) Gray (pl. 1a, b). The orchids are still present and do not appear to be grazed by rabbits, perhaps partly because leaves now tend to remain at the bryophyte vegetation surface, rather than extending upwards.

The populations at other sites along the northwest featherbed (Half Moon Bay to Boiler Rocks, fig. 1) are much smaller. Here the populations of *N. dienemum* occur in sheltered locations at the base of the escarpment or near the base of rock stacks, most often under *Stilbocarpa* leaves. The population at Eagle Cave was the first to be recorded, by Nigel Brothers in 1976.

At Bauer Bay, a well-observed population of *N. dienemum* occurs near the hut on approximately 10 m x 10 m of open waterlogged ground vegetated with bryophytes and previously a few *Stilbocarpa* plants (now removed by rabbit overgrazing). Towards the southern end of Bauer Bay, near Gentoo Flats, an additional small orchid population was found during early 2009 (P. Bricher and J. Wasley, pers. comm.) and we confirmed this species as *N. dienemum* in March 2009.

Towards the north of Bauer Bay basin, near the track leading to Emerald Lake, a small orchid population was observed in 1979. Further south along the west coast, at each of Aurora Cave, Aurora Point near the base of the escarpment, and inland of Cormorant Point about 100 m west of the escarpment base, small colonies have been seen growing in the shelter of *Stilbocarpa* leaves. None of these populations could be located either in summer 2004 or 2006, so neither the population sizes nor species are known, although *N. dienemum* seems most likely.

At Green Gorge, several small *N. dienemum* populations are known in the mire, growing in extremely wet conditions; the largest of these sub-populations is spread over an area of probably 50 m x 50 m but is difficult of access due to the extremely wet conditions.

Populations of *N. sulcatum*

Orchids were first observed in the Sawyer Creek valley in the late 1970s (GRC), and later were described as *Nematoceras sulcatum* (Mackenzie *et al.* 2005, Clements & Jones 2006, Clements *et al.* 2007) (pl. 2a). One population of *N. sulcatum*, 1.2 km south of Green Gorge in the Sawyer Creek valley, on the eastern side of the valley south of the waterfall, comprises sparsely-scattered plants in an area approximately 6 m x 3 m, with a few additional plants some 20 m further south

Table 1
Population details for *Nematoceras* spp. on Macquarie Island

Site no.	Species	Location name (year first observed)	Latitude longitude	Area (m ²)	Colony size (plants)	Notes
1	<i>N. dienemum</i>	Handspike Corner (1980)	54°29'51"S 158°53'18"E	10 000	5000+	Numerous sites between rocky coast and halfway to escarpment
2	<i>N. dienemum</i>	Half Moon Bay (1977)	54°30'43"S 158°53'14"E	1000+	500+	Several sites near base of escarpment
3	<i>N. dienemum</i>	Elizabeth and Mary Point (1980)	54°30'50"S 158°52'42"E	Not known	Not known	Site near base of escarpment, orchids locally common
4	<i>N. dienemum</i>	Eagle Point	54°31'0"S 158°53'14"E	Not known	Not known	Colonies sparsely scattered over small area, orchids amongst mosses
5	<i>N. dienemum</i>	Eagle Cave (1976)	54°31'19"S 158°52'8"E	Not known	Not known	Site of first observation of orchids 1976
6	<i>N. dienemum</i>	Langdon Bay (2005)	54°31'48"S 158°52'21"E	600	Not known	Site near base of escarpment
7	<i>N. dienemum</i>	Douglas Bay (1984)	54°32'24"S 158°52'7"E	100	Not known	Several sites near base of escarpment
8	<i>N. dienemum</i>	Boiler Rocks (1979)	54°32'42"S 158°52'16"E	20+	500+	Several sites between coast and base of escarpment
9	<i>Nematoceras</i> sp.	North Bauer Bay (1979)	54°32'56"S 158°52'46"E	Not known	Not known	
10	<i>N. dienemum</i>	Bauer Bay hut (1979)	54°33'20"S 158°52'37"E	100	500	To south east of hut
11	<i>N. dienemum</i>	Gentoo Flats (2009)	54°33'30"S 158°52'24"E	20	100	
12	<i>Nematoceras</i> sp.	Cormorant Point (1978)	54°34'10"S 158°51'56"E	Not known	Not known	Site near base of escarpment
13	<i>Nematoceras</i> sp.	South of Aurora Cave (1977)	54°35'34"S 158°50'43"E	Not known	Not known	
14	<i>Nematoceras</i> sp.	Aurora Point (1984)	54°37'18"S 158°50'18"E	Not known	Not known	Orchids quite common
15	<i>N. sulcatum</i>	Red River (2006)	54°36'12"S 158°53'40"E	100	300	
16	<i>N. sulcatum</i>	Green Gorge North Basin (1984)	54°37'37"S 158°53'8"E	2000	1300+	Two sites approx. 100 m apart
17	<i>N. dienemum</i>	Green Gorge Mire (1980)	54°37'47"S 158°53'35"E	2500	1000+	In mire, west of tarn
18	<i>Nematoceras</i> sp.	South West Green Gorge (1980)	54°38'3"S 158°53'7"E	Not known	Not known	
19	<i>N. sulcatum</i>	Sawyer Creek (1980)	54°38'25"S 158°53'1"E	40	1000	
20	<i>N. sulcatum</i>	Pyramid Peak (1980)	54°39'9"S 158°52'47"E	250	10 000+	

(fig. 1, table 1). Another population, a further 2.9 km to the south and about 700 m north of Pyramid Peak, is very much larger, comprising many thousands of plants and occupying an area of some 5 m x 50 m. In a single square metre quadrat in December 2006, we counted over 1100 distinct orchid leaves in the site near Pyramid Peak, and there were many similarly dense areas at this location.

A thorough search of potential orchid habitats confirmed two additional adjacent populations of orchids north of Green Gorge, first observed in the 1980s (GRC) but until now, undescribed (pl. 2c). They are located very close together, and are shown as a single population at Green Gorge North (Site 16 on fig. 1, table 1) some 200 m to 300 m west of the Overland walking track, approximately 1.3 km northwest of Green Gorge hut. This population is not within the Green Gorge basin and mire, but is upstream

and uphill to the north. It has clearly not been dispersed by water from the large and widespread population of *N. dienemum* that occurs within the Green Gorge mire.

Searches for new orchid locations also led to the discovery of a population in the Red River valley (site 15, fig. 1, pl 2d), approximately 3.3 km north of Green Gorge, 100 m east of the Overland walking track. The orchids are scattered over a site some 5 m x 20 m, at approximately 100 m a.s.l. In early 2007 the population was estimated at several hundred plants, including many that were flowering.

The orchids in the two new Green Gorge North and Red River valley populations appear morphologically very similar to *N. sulcatum* from sites in the Sawyer Creek valley, south of Green Gorge, although the Green Gorge North orchids have somewhat more fleshy leaves (pl. 2).



PLATE 1

Nematoceras diemum leaves, flowers and habitat. a. leaves at Handspike, sheltered by *Stilbocarpa* in 2004. Orchid leaves are approximately 1.5–2 cm in length; b. leaves at Handspike, in the absence of *Stilbocarpa* protection, in 2007; c. mature seed capsules at Bauer Bay. Orchid leaves are approximately 1.5 cm in length; seed capsules extend 5 cm above surface vegetation; d. flower at Handspike; leaf is approximately 1.7 cm in length.



PLATE 2

Nematoceras sulcatum leaves, flower and habitat. a. flower in the Sawyer Creek valley; leaf is approximately 1.7 cm in length; b. leaves and flower in the Green Gorge North basin; leaf is approximately 1.8 cm in length; c. flower in the Green Gorge North basin; leaf is approximately 1.8 cm in length; d. flowering plant from Red River; leaf is approximately 1.8 cm in length.



PLATE 3.

A single plant of Nematoceras dienemum from Bauer Bay, observed daily, and showing progression of the flower from bud to mature seed capsule without the flower ever opening. a. Flower buds emerging; late September; b. flowers remained as buds for several weeks, never opening or extending; late October; c. immature capsule (foreground), and shrivelled failed flower (background); late November; d. maturing and extending capsule; mid-December; e. mature capsule; late December; f. split capsule shedding seeds (visible on leaf); late December. Leaf is approximately 1.7 cm in length; capsule is 1.2 cm in length on a 2.7 cm stalk.



PLATE 4

Leaves of *Nematoceras dienemum* at Bauer Bay showing white mosaic symptoms, possibly indicating infection with a plant virus. Affected leaves are approximately 1.2–2.3 cm in length.

Additional population

At the southern end of Green Gorge mire, west of the outflow of Sawyer Creek into the mire, at about 20 m a.s.l. (only marginally higher than the population within the mire), a population of orchids has been reported (called Southwest Green Gorge in table 1; site 18 on fig. 1) which it was not possible to reach in summer 2004, during 2006–07 or in summer 2008–09. It is not known whether this is a population of *N. dienemum*, dispersed (perhaps by birds or wind) from the extensive population further north in the Green Gorge mire, or whether it is an additional population of *N. sulcatum*, dispersed downstream by water, wind or birds from populations further up the Sawyer Creek valley. This site is impossible to reach on foot unless the season is unusually dry, and we have not been able to access it in the past few years to confirm the species.

Habitats

Our field studies (between 1977 and 2009; table 1) confirm the different habitats described for the two Macquarie Island orchid species (Clements *et al.* 2007). *Nematoceras dienemum* is known from sites along the west coastal terraces, between Handspike Corner and Aurora Cave, from the Bauer Bay basin, and from the Green Gorge mire. All sites are less than 30 m above sea level, with bryophyte-dominated quaking mire or herb- and moss-dominated mire vegetation.

Several of the more accessible populations of *Nematoceras* have been monitored on an opportunistic basis over the past 20 years, including those at Bauer Bay, Handspike Corner and Sawyer Creek valley. Reports that these orchid colonies can “move” is probably due to the fact that just a few (if any) leaves are visible above ground at certain times of year (*Nematoceras* spp are not “winter green” *sensu* Sørensen 1941), but also in part to major site disturbance. For example, we have observed that a dense but small sub-population in a 3 m x 2 m site at Bauer Bay which was thriving in early 2004 (with at least 100 seed capsules), in early 2006 was a deep muddy wallow made by the Southern Elephant Seal, *Mirounga leonina* (Linnaeus, 1758), and devoid of surface

vegetation. Late in 2006, when disturbance by elephant seals had diminished, a few apparently healthy orchid tubers were observed under bryophyte cover near the seal wallow. In early January 2007, with the wallow no longer in use, a few leaves appeared at its edge, and in late January, orchids were in flower one metre from the wallow. The orchids had not been destroyed by the disturbance but had simply been pushed aside with the loose mire vegetation in the waterlogged soil.

In contrast, *N. sulcatum* populations apparently occur in at least four separate sites on the plateau uplands at 80–150 m a.s.l., in seepage areas along the eastern side of the Sawyer Creek valley, beside drainage lines in the Green Gorge North basin, and in the Red River basin near drainage lines leading into a small lake and Red River. At all four sites the water table is close to the surface, with drainage towards Red River tributaries, Green Gorge mire and Sawyer Creek. The vegetation is short herb vegetation dominated by *Festuca contracta* Kirk, *Agrostis magellanica* Lam. and *Luzula crinita* Hook.f., with a mixture of bryophytes.

Life histories

Macquarie Island orchids generally appear above ground only in spring and summer between September and early April, with flowering generally occurring between November and January. Leaves have occasionally been observed as early as the end of August, but only within the bryophyte vegetation and not unfurled. In most years, many leaves appear during October. Flowering has only been reported between November and January, with immature and ripe seed capsules being observed in *N. dienemum* populations between January and March. Dying leaves have also been observed as late as April for both species.

Flower development in *N. dienemum*

We have followed the daily progression of two single flowers of an *N. dienemum* Bauer Bay plant over three months from September (pl. 3). Neither flower progressed from the bud stage, and one shrivelled and died within a few weeks. However, we observed that although the second flower bud also never opened, a seed capsule formed and ripened with shedding of many seeds (pl. 3f), though viability was not tested.

Seasonal variability in *N. dienemum*

Most of our visual observations of orchid populations have been made on an opportunistic basis. Between January and March 2004 numerous seed capsules were observed in orchid populations at Bauer Bay (pl. 1c), Handspike Corner and Green Gorge mire. Between late November 2006 and February 2007, many of the orchid populations flowered on Macquarie Island, including those at Green Gorge, Handspike Corner (pl. 1d) and Bauer Bay (fig. 1). However, it appeared that many of the flowers failed to open, or failed to set seed, and only around 10% of the flowers were observed to form capsules. No orchids were observed with flowers or seed capsules on Macquarie Island in the 2007/2008 summer at Bauer Bay, or elsewhere. In late March 2009, one ripe seed capsule was observed at Gentoo Flats, more than 50 were seen at Bauer Bay (some shedding seeds, some unripe and just starting to elongate) and many unripe capsules were observed at Green Gorge mire.

Seasonal variability in *N. sulcatum*

Between January and March 2004 neither flowers nor capsules were observed in the Sawyer Creek valley or Pyramid Peak populations. However, in the summer of 2006–07 the populations near Pyramid Peak, Sawyer Creek valley (pl. 2a), Green Gorge North (pl. 2b, c) and Red River (pl. 2d) all flowered.

More detailed observations during 2006 showed that by early November, buds and flowers were appearing in most populations. By mid- to late November, some 30% of plants in the Pyramid Creek, Sawyer Creek valley and Green Gorge North populations were flowering, and the Red River population had flower buds. In mid-January the Red River population was still flowering. Unfortunately, it was not possible to visit flowering populations later in that season to observe whether seed capsule formation had occurred.

No flowers were seen in any populations in summer 2007–08. In December 2008 a few plants flowered at Pyramid Peak, but no capsules were seen in any of the *N. sulcatum* populations in March 2009.

Leaf mosaic symptoms

At both Bauer Bay and Handspike Corner, a few leaves of *N. dienemum* have been observed with a striking white mosaic, similar to symptoms of viral disease (pl. 4). At one site at Bauer Bay, such leaves have been noted in three separate years at the same location. Whether these orchids are infected with a plant virus, or have a genetic alteration leading to mosaic symptoms remains to be analysed, but any virus is likely to be unrelated to the only plant virus reported from Macquarie Island, Stilbocarpa mosaic bacilliform virus, SMBV (Skotnicki *et al.* 2003). Similar white mosaic markings have also been observed on leaves of *Cardamine corymbosa* Hook.f. at two locations on the island in three separate years: these also have yet to be analysed for cause of the symptoms.

DISCUSSION

Populations and habitats

Eleven populations confirmed as *N. dienemum* are now known on Macquarie Island. The largest population is at Handspike Corner with perhaps 5000 plants; nine smaller populations are known from locations further south along the western coastal terrace, and one extensive population is known from the eastern coast in the mire at Green Gorge (fig. 1, table 1). In addition, a further four orchid populations have been observed along the western coastal terrace, and it seems most likely these will also be *N. dienemum*. Our observations confirm two previously described populations of *N. sulcatum*, and have located two additional populations believed to be *N. sulcatum*. The two populations in Sawyer Creek valley (fig. 1, table 1), are found, as Clements *et al.* (2007) describe, amongst moist short herb vegetation dominated by graminoids and bryophytes. The populations in the Green Gorge North Basin and Red River valley are in similar vegetation with the water table close to the surface along a drainage line. All are between 80 m and 100 m a.s.l.

Life histories

The leaves of *Nematoceras dienemum* and *N. sulcatum* die back annually, and new leaf growth appears in spring. During the winter, *N. dienemum* plants are protected by the bryophytes and other mire plants, and *N. sulcatum* by the graminoid plants amongst which they grow. They have storage tissue in roots and tubers via which vegetative reproduction occurs. They fit the usual pattern of hemicryptophyte plants (Raunkiaer 1934) which are commonly herbaceous perennials found in cold moist climates.

Reproduction in *Nematoceras*

Nematoceras orchids reproduce vegetatively by production of daughter tubers on stolons, and sexually by forming seeds following pollination (Clements *et al.* 2007).

The estimates of population sizes in table 1 are based on the number of leaves above ground in summer, since each *Nematoceras* plant has only a solitary leaf above ground (Clements & Jones 2007). However, because the species can grow vegetatively from tubers, clumps (or colonies) of plants will be clonal. It is not possible to say how many genetically distinct individuals are represented in the population, but it is likely to be considerably fewer than the number of leaves. Flowers have been observed at some locations in some years, but the number of flowers is vastly smaller than the number of leaves in any area. It is not possible to say from our observations what proportion of the plants (leaves) that have been observed represent reproductively mature individuals capable of flowering and setting seed. Both the floral morphology of *N. dienemum* and the friable nature of the pollen (Clements & Jones 2007) are consistent with the possibility of autogamy (self-pollination), a feature of life histories of plants in isolated or extreme environments. The numerous maturing seed capsules observed in the field in summer 2004 were taken as an indication of autogamy, but alternatively could indicate presence of an active pollinator (Clements *et al.* 2007). Although our daily observations of flower development over three months (pl. 3) were made on only two flowers, they confirm that autogamy, specifically cleistogamy (self-pollination in unopened flowers), can occur in *N. dienemum*.

We have no observations concerning the mode of pollination in *N. sulcatum*. No *N. sulcatum* seed capsules have yet been seen (perhaps because no observer has been in the right place at the right time, or perhaps because they are not formed), although the flower structure of this orchid appears consistent with insect pollination. The timing of flower and capsule development of both *N. dienemum* and *N. sulcatum* is comparable to the reproductive behaviour of the large herbs *Stilbocarpa polaris* and *Pleurophyllum hookeri* Buchan. on Macquarie Island: perennials with slow to very slow phenology, and extensive storage tissues (Bergstrom *et al.* 1997). Although nothing is known of their rate of seed germinability, the orchids can, like *S. polaris* and *P. hookeri*, be regarded as perennial stayers (*sensu* During 1979, Bergstrom *et al.* 1997).

It is clear that there is considerable variability in the extent of flowering from year to year. The summers of 2003–04 and 2006–07 were “good” flowering seasons for *N. dienemum*; 2007–08 was a “poor” one. For *N. sulcatum*, summer 2006–07 was a good flowering season; 2003–04 and 2007–08 were poor ones. At this stage we do not know the determinant for good or bad flowering seasons in

these orchids. Similarly, the megaherb daisy, *Pleurophyllum hookeri*, does not flower annually on Macquarie Island, and the determinant for flower initiation is not known.

Although temperatures on the island are low and windspeeds are high, moisture for plant growth is available all year (Pendlebury & Barnes-Keoghan 2007). Plant productivity, as measured in closed vegetation dominated by *Poa foliosa* (Hook.f.) Hook.f., *Stilbocarpa polaris* and *Pleurophyllum hookeri*, is high (Jenkin & Ashton 1970, Jenkin 1975, Hnatiuk 1978). Nevertheless, for *S. polaris* and *P. hookeri*, despite their high biomass production, completing the sequence from flower initiation to seed and fruit maturity appears to take longer than one season, implying the presence of pre-formed flower buds that overwinter (Bergstrom *et al.* 1997). Similarly, for *N. sulcatum* where buds and flowers were observed in early November, only a few weeks after leaves appeared, it is likely that pre-formation of flower buds is involved; this seems likely also for *N. dienemum*. For plants with overwintering flower buds, environmental conditions in the one or two summers preceding flowering influence flower bud initiation (Mark 1970, Billings 1974). In addition, it may be that flowering and setting seed at two- or three-year intervals is more metabolically sustainable than annually.

Origin and dispersal of Macquarie Island orchids

Two separate long-distance over-ocean dispersals by wind or birds from New Zealand seem the most likely means by which ancestors of the two endemic species of *Nematoceras* reached Macquarie Island followed by on-island evolution and dispersal (Clements *et al.* 2007). Although long-distance dispersal (LDD) events over distances of greater than 250 km are hypothesised to occur only once in more than one million years under the mean trend, they may occur far more frequently as a result of processes or events that "break the rules". Such "non-standard" mechanisms include extreme climatic events, prolonged turbulent updrafts and cyclonic activity (Nathan 2008), phenomena that are certainly part of sub-Antarctic weather patterns (Streten 1988). Genetic studies of plants from Svalbard and surrounding Arctic regions have shown the source populations for post-glacial, Holocene plant colonisation of Svalbard ranged from Greenland to northwestern Russia. Probable vectors include wind. Dispersal mechanisms of the early to mid-Holocene are likely still to be operating today, and LDD can be assumed still to occur with regularity in Arctic and other regions (Alsos *et al.* 2007).

Humans are unlikely to have played a role in the introduction of orchids to Macquarie Island, because populations of *N. dienemum* tend to be found distant from the main centres of habitation on the island, in very wet and boggy "featherbed" areas which are difficult to cross on foot and therefore usually avoided (Brown *et al.* 1978). For the same reasons humans are unlikely to have been agents of dispersal for *N. dienemum* around the island.

Similarly, humans are unlikely to have dispersed *N. sulcatum* around Macquarie Island. Although three of the known populations occur very near the sole Overland walking track which runs down the length of the island, they are located well away from parts of the island most frequently visited, high on the plateau and some distance from the coast. The orchid populations in the Green Gorge North Basin, which occur in similar vegetation to the Sawyer Creek populations, are far away from any walking

track in very wet ground difficult to cross. We were unable to reach these populations in 2007 due to the high level of the water table that season.

Bergstrom *et al.* (2006) argue that, for *Poa litorosa* Cheeseman and *Carex trifida* Cav., two species found elsewhere but with restricted distributions on Macquarie Island, the largest populations at Handspike Point constitute the founder populations. Similarly, it could be suggested that the extensive population of *N. dienemum* at nearby Handspike Corner is the founder population for this species, in the sense that this is a likely site for first arrival of the ancestral propagule(s) from which *N. dienemum* developed, and subsequently dispersed to its other sites around the island.

For *N. dienemum*, dispersal around the island could be either by seed, windblown from the capsules which are held erect on a thickened peduncle 4–8 cm long (Clements & Jones 2007), or via dispersal of their globose to ellipsoid vegetative tubers, 1–5 mm in diameter. *N. sulcatum* similarly has globose to ellipsoid tubers; 1–7 mm long by 1–6 mm wide. For seeds to germinate, they would need to encounter the appropriate fungus with which to establish a mycorrhizal association. The identity of the fungus is not yet known for either species, but it is likely to be widespread in Macquarie Island mires and moist short herb vegetation.

For normally subterranean tubers to be dispersed away from the original clump of orchids, they would need to be detached and brought to the surface. Such disturbance of orchid plants has been noted and presumed to be by birds, probably Weka, *Gallirallus australis scotti* (Ogilvy-Grant, 1905) or Kelp Gulls, *Larus dominicanus* Lichenstein, 1823, seeking to eat the tubers and fleshy roots (Brown *et al.* 1978, Copson 1984). Weka, introduced from Stewart Island in 1867 (Cumpston 1968), were eradicated from Macquarie Island in 1988 (Copson 1995, Copson & Whinam 2001). They were on the island for a little over 100 years, replacing the ecologically very similar Macquarie Island subspecies of the Pacific Banded Rail, *Rallus philippensis macquariensis* Hutton, 1879, which became extinct in the late nineteenth century. Although usually described as flightless, at Macquarie Island it was a capable though reluctant flier. Given appropriate atmospheric conditions, it could well have flown or been blown from one mire site to another on the island, very possibly with seeds or tubers stuck in mud on feet or feathers.

Other birds, indigenous to the island, also scabble amongst mire and moist closed short vegetation, presumably seeking terrestrial invertebrates as food: for example Dominican (Kelp) Gulls (Selkirk *et al.* 1990, Parks and Wildlife 2006) and ducks (Black Duck, *Anas superciliosa* Gmelin, 1789, Mallard *Anas platyrhynchos* Linnaeus, 1758). Dominican (Kelp) Gulls are known to congregate on the flats below and to the north of Pyramid Peak, at the head of the Sawyer Creek valley. Brown Skuas, *Catharacta lonnbergi* Mathews, 1912, have been observed turning over moss polsters in feldmark, presumably foraging for invertebrates such as worms and slugs (Selkirk *et al.* 1990). Skuas congregate adjacent to some lakes on the island where they bathe and groom themselves; the surrounding moist closed short herb vegetation can become quite disturbed by the amount of skua traffic across it. We have observed disturbance of a *N. dienemum* site near Bauer Bay hut by wallowing elephant seals, as described above. Once dislodged, tubers could be moved to new sites on the island over short distances by wind, and over longer distances entangled on birds.

In an investigation of floral phenology in the South Georgia vascular flora, Walton (1982) found many of the adaptations to cold summer climates described by Billings (1974) for plants of high latitude and alpine regions. Both species of *Nematoceras* similarly exhibit life history strategies well suited to life in the sub-Antarctic environment:

- they are perennial
- they are capable of vegetative reproduction from tubers
- although not winter-green (*sensu* Sørensen 1941) they have storage roots and tubers from which spring vegetative growth can be supplied
- their tubers and overwintering meristems are well protected, just below the surface of surrounding bryophyte and graminoid vegetation
- we infer that flower buds are pre-formed in the season preceding flowering
- *N. dienemum* can be autogamous and cleistogamous, though may also be capable of insect pollination. Such information is not known for *N. sulcatum*.

Although *N. dienemum* and *N. sulcatum* live and reproduce successfully in the isolated, sub-Antarctic environment, these species are considered vulnerable (*N. dienemum*) and endangered (*N. sulcatum*) species under the Tasmanian Threatened Species Act of 1995 as their numbers are low and they are confined to the northern half of Macquarie Island. Looking back, the presumed on-island evolution from two separate arrivals of two separate ancestors makes these two endemic orchid species fascinating. Looking forward, they will continue to be fascinating as we learn more about their biology, and as we observe the way in which the populations and the species respond to environmental change, particularly the temperature increase and variation in available moisture (Pendlebury & Barnes-Keoghan 2007) that is occurring in the sub-Antarctic.

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FRESHWATER DIATOMS ON SUB-ANTARCTIC MACQUARIE ISLAND: AN ECOLOGICAL SURVEY OF 14 LAKES

by T. P. McBride

(with two text-figures, three tables and three appendices)

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A survey of the diatom (Bacillariophyceae) populations in 14 lakes and ponds on sub-Antarctic Macquarie Island identified 102 species from 34 genera, including species considered endemic to the sub-Antarctic region. Multivariate analysis of the diatom communities divided the lakes into two broad groups; oligotrophic plateau lakes dominated by species including *Brachysira exilis*, *Fragilaria capucina* var. *gracilis*, *Psammodium abundans*, *Ps. confusum* and *Ps. confusum* var. *atomoides*, and lowland peat-based lakes dominated by species including *Fragilaria pulchella*, *Planorhynchium lanceolatum* and *Pl. quadripunctatum*. Factors relating to lake elevation rather than water pH or conductivity appeared to have most influence on the lake diatom communities.

Key Words: Macquarie Island, sub-Antarctic, diatoms, Bacillariophyceae.

INTRODUCTION

Sub-Antarctic Macquarie Island (fig. 1) is located at 54°38'S, 158°53'E, approximately midway between Australia and the Antarctic continent within the sub-Antarctic biogeographical zone, a region of islands in the southern Atlantic and Indian oceans. Macquarie Island is politically part of Tasmania and is listed as a World Heritage Area because of its geological and natural significance. The island is part of an undersea ridge raised above the surface by tectonic action and the nearest large land masses are mainland Tasmania, approx 1470 km NNW, and New Zealand approx 1130 km NE (Commonwealth of Australia 1996). An undulating plateau generally 200–250 m above sea level covers most of the island's 34 x 5.5 km area. The climate is moist, windy and cool (yearly average 5°C) with low seasonal variation (Selkirk *et al.* 1990). Numerous lakes and extensive waterlogged areas are present. The lake waters are of low salinity, which is mostly derived from sea spray (Tyler 1972). This paper presents findings from the first extensive survey of the diatoms in freshwater habitats on Macquarie Island and compares these findings with surveys on other sub-Antarctic islands. Diatoms are unicellular algae characterised by silica cell walls consisting of two overlapping halves called valves. Diatom taxonomy is based on the shape and patterning of the valves rather than the living forms. Diatoms inhabit marine, freshwater and moist terrestrial environments throughout the world. The structure of diatom communities is sensitive to water quality and diatoms can provide a powerful tool for assessing and monitoring water quality and environmental conditions. The presently available literature on sub-Antarctic diatoms identifies floras containing a number of endemic taxa and many similarities exist between diatom floras of widely scattered islands (Van de Vijver & Beyens 1999). Diatom studies are available for Kerguelen Island: (Germain 1937, Bourrelly & Manguin 1954, Le Cohu 1981, Le Cohu & Maillard 1983, 1986, Van de Vijver *et al.* 1998); Crozet Isles (Pierre 1977, Van de Vijver & Beyens 1999, Van de Vijver *et al.* 2002); and Heard Island (Van de Vijver *et al.* 2004). The available publications on Macquarie Island diatoms (Bunt 1954, Evans 1970, Keenan 1995, McBride

& Selkirk 1999, McBride *et al.* 1999 and Saunders *et al.* 2008) do not include a comprehensive illustrated flora.

SAMPLES AND ANALYTICAL METHODS

Rock scrapings, submerged vegetation and bottom sediment were collected from 14 lakes and ponds (table 1) during summer visits to Macquarie Island (details in appendix 1). Samples of 15–25 ml were taken within a 10–40 cm depth range near the shore and preserved with formaldehyde until processed. The submerged vascular plant *Myriophyllum triphyllum* Orchard was present in most lakes and was included in collections as a diatom substrate. Rock surfaces for scraping were not available in the peat-based lakes. Water pH, conductivity and temperature were measured at the time of sample collection and water samples were taken for later analysis. Figure 1 shows the location of the lakes and ponds from which collections were made. Of the 26 named water bodies on the island, the 14 sampled included representative types spanning most of the island. Water bodies on Macquarie Island are variously named as lake, lagoon, pond or tarn but for simplicity in this paper the water bodies sampled are all referred to as lakes. Evans (1970) proposed a classification system for Macquarie Island water bodies that can be used to categorise the lakes in this study. Duck Lagoon, Green Gorge Tarn, Handspike Tarn and Langdon Point Pond are type "a", peat-based ponds on the coastal terrace; Brothers Lake, "S" Pond, Skua Lake and Square Lake are type "b" ponds occurring on highmoor peat beds on the plateau; Lake Ainsworth, Ifould Lake, Major Lake, Prion Lake, Pyramid Lake and Tulloch Lake are type "c" lakes occurring on tundra soils on the plateau. Major Lake is the island's largest lake, having an area of 0.5 km² and maximum depth of 16 m. "S" Pond is tiny compared with the plateau lakes (max width about 10 m, max depth about 40 cm) but was included in the sampling program because Evans (1970) used it as a study site and listed its diatom flora.

To prepare the diatom material for examination, about 20 ml of 34% hydrogen peroxide was added to the sample in a covered vial and left at room temperature for at least a week to partially oxidise the material without violent

TABLE 1
Sampling sites and number of samples collected
per year from 1988 to 1993

Year	Lake Ainsworth	Brothers Lake	Duck Lagoon	'S' Pond	Green Gorge Tarn	Handspike Tarn	Ifould Lake	Langdon Point Pond	Major Lake	Pyramid Lake	Prion Lake	Skua Lake	Square Lake	Tulloch Lake
1988	2	3	1		1				3	2		4		2
1989	5	3	8	2	1	2	3	2	3	-	1	3		
1990		2	4	1	1				1	1	1		2	2
1991		1	2		1						1		2	
1992		3		1						2	2		4	4
1993	1				1				2					2

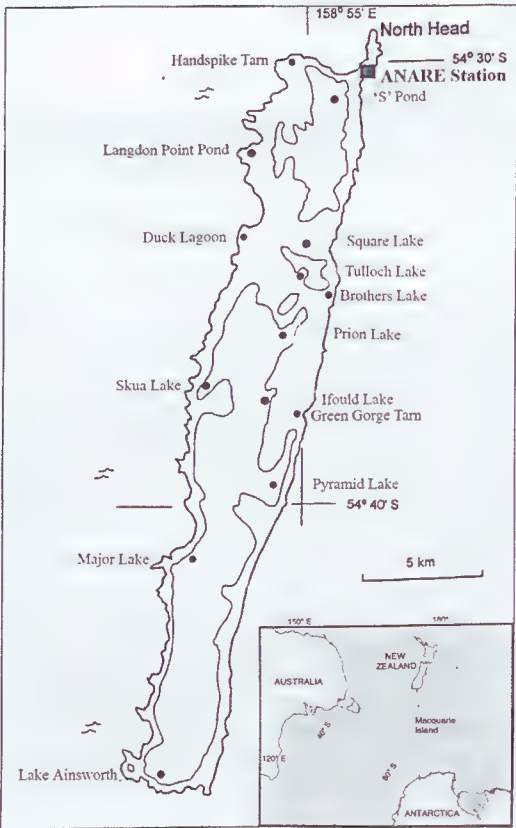


FIG. 1 — Macquarie Island, showing locations of lakes and ponds that were sampled.

reaction. Oxidation was completed by placing the vial in an oven at 100°C for 15 minutes. The cleared diatom valves were allowed to settle on to a cover slip from suspension then mounted in Naphrax on a microslide (McBride 1988). At least 300 valves were identified and counted on each microslide. Species were identified at 1000x magnification under a light microscope (Olympus Vanox) fitted with Nomarski interference contrast. The principal taxonomic reference was that of Van de Vijver *et al.* (2002) because of its sub-Antarctic specificity and status as the only comprehensive illustrated flora for a sub-Antarctic island. Other taxonomic

references were Krammer & Lange-Bertalot (1997), Germain (1981), Le Cohu (1981), Le Cohu & Maillard (1983, 1986) and John (1983). Recent revisions of diatom taxonomy have been incorporated to maintain consistency with Van de Vijver *et al.* (2002) and these changes considerably rearrange the genera, e.g., *Achnantheidium*, *Planothidium* and *Psammothidium* have been separated from *Achnanthes*, and *Adlafia*, *Diadesmis*, *Naviculadicta*, *Lecohuia*, *Eolimna*, *Geissleria*, *Luticola* have been separated from *Navicula*. The similarity of the diatom community in the same lake in different years was assessed using Twinspan ordination (Minchin 1990), where the samples were arranged in an order determined by the relative abundance of each diatom species in the sample (appendix 1 lists samples in the Twinspan order). For six of the lakes ('S' Pond, Major Lake, Skua Lake, Duck Lagoon, Handspike Tarn and Langdon Point Pond) the samples from each lake grouped together without mingling with the samples from other lakes. For the other lakes some intermingling of samples from different lakes occurred but generally the samples from each lake were grouped together. Therefore it was considered appropriate to combine the data from each lake for further analysis. Multivariate analysis using Decorana (Minchin 1990) was used to align the lakes along theoretical environmental gradients based on similarities in their diatom communities.

RESULTS

Over 32 000 diatom valves were counted in samples from the 14 lakes and a total of 102 species in 34 genera were identified (details in appendix 2). Figure 2 shows the arrangement of the lakes when Decorana Axis 1 is plotted against Axis 2. Table 2 and appendix 3 show the major species observed in each lake with the order of the lakes according to Axis 1 of the Decorana ordination. The high Eigenvalue of Axis 1 (0.79) suggests this ordering of the lakes relates to a strong environmental gradient. Four of the plateau lakes – Lake Ainsworth, Prion Lake, Pyramid Lake and Tulloch Lake – are grouped together, as are Major Lake and Skua Lake. Ifould Lake and Square Lake are placed towards the group of coastal terrace lakes. The coastal terrace lakes – Brothers Lake, Duck Lagoon, Green Gorge Tarn, Handspike Tarn and Langdon Point Pond – form a closely spaced group suggesting their communities are very similar. 'S' Pond is an outlier especially when its position on Axis 2 is taken into account.

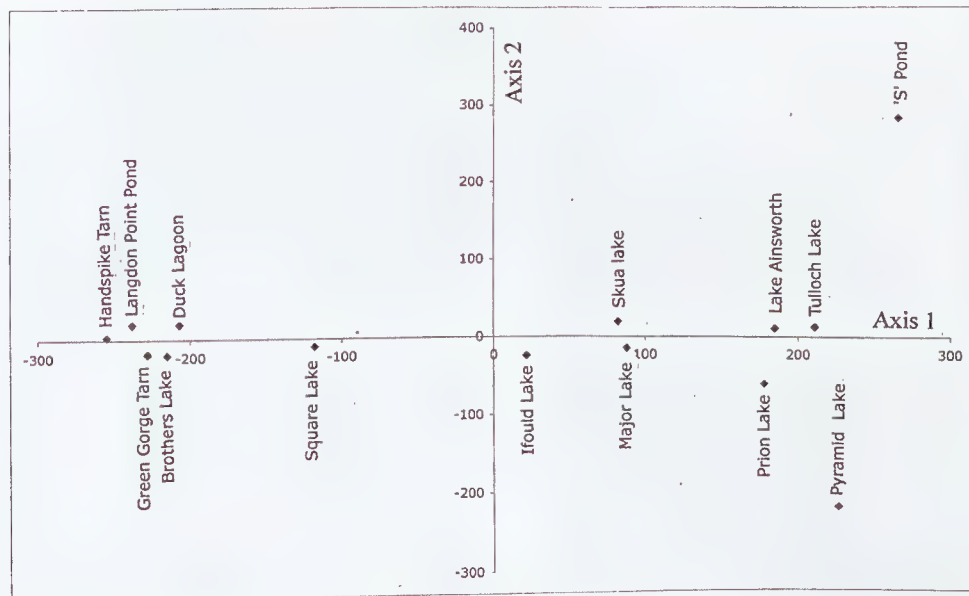


FIG. 2 — Arrangement of lake diatom communities along environmental gradients. Decorana Axis 1 (Eigenvalue 0.79) plotted against Axis 2 (Eigenvalue 0.49) showing the positions of lake diatom communities in this theoretical space. All species were included and data were the relative abundance of each species without transformation. These ordination axes represent environmental gradients that influence the structure of the diatom communities.

TABLE 2
Diatom species in Macquarie Island lakes

	'S' Pond	Pyramid Lake	Tulloch Lake	Lake Ainsworth	Prion Lake	Major Lake	Skua lake	Ifould Lake	Square Lake	Duck Lagoon	Brothers Lake	Green Gorge Tam	Langdon Point Pond	Handspike Tam
<i>Achnanthes minutissimum</i>	-	-	-	-	-	##	##	###	#	-	-	-	-	-
<i>Amphora coffeaeformis</i>	###	-	-	-	-	-	-	-	###	-	-	-	-	-
<i>Aulacoseira distans</i>	###	#	###	###	#	-	-	-	-	-	-	-	-	-
<i>Brachysira exilis</i>	###	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Cocconeis placentula</i>	-	-	-	-	-	-	-	##	##	###	##	##	-	-
<i>Cymbella microcephala</i>	-	-	-	-	-	-	-	##	-	-	-	-	-	-
<i>Diatomella balfouriana</i>	-	-	-	-	-	-	##	##	-	-	-	-	-	-
<i>Eumotia curvata</i>	-	###	-	-	#	-	-	-	-	-	-	-	-	-
<i>Fragilaria capucina</i> var <i>vaucheriae</i>	-	-	-	#	-	##	##	#	###	##	#	-	##	-
<i>Fragilaria capucina</i> var <i>gracilis</i>	-	###	###	###	###	###	###	-	-	-	-	-	-	-
<i>Fragilaria capucina</i> var <i>rumpens</i>	-	-	-	##	-	-	-	-	-	-	-	-	-	-
<i>Fragilaria exigua</i>	-	-	-	-	-	-	-	-	-	###	-	-	##	-
<i>Fragilaria pulchella</i>	-	-	-	-	-	##	-	###	###	##	###	###	-	###
<i>Gomphonema affine</i>	-	-	-	-	-	-	-	-	#	-	###	-	-	-
<i>Gomphonema intricatum</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Lecothia geniculata</i>	-	-	-	-	##	-	-	-	-	-	-	-	-	-
<i>Naviculadicta seminulum</i>	-	-	-	-	#	-	-	-	-	-	-	-	##	#
<i>Nitzschia gracilis</i>	-	-	-	-	-	-	-	-	###	#	##	-	-	-
<i>Planothidium aueri</i>	-	-	-	-	-	-	-	##	-	-	-	-	-	-
<i>Planothidium deliculatum</i>	-	-	-	-	-	-	-	-	-	##	-	-	###	-
<i>Planothidium lanceolatum</i>	-	-	-	-	-	-	-	-	-	#	#	###	###	###
<i>Planothidium quadripunctatum</i>	-	-	-	-	-	-	-	-	-	###	##	#	###	###
<i>Psammothidium abundans</i>	###	-	###	-	-	#	###	-	-	-	-	-	-	-
<i>Psammothidium confusum</i>	-	##	###	##	###	#	-	###	-	-	-	-	-	-
<i>Psammothidium confusum</i> var <i>atomoides</i>	-	###	###	#	##	#	-	#	-	-	-	-	-	-
<i>Psammothidium oblongellum</i>	-	-	-	-	-	-	-	-	-	-	-	-	##	-
<i>Psammothidium therezienii</i>	###	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Staurosira pinnata</i>	-	-	-	-	-	-	###	-	-	##	-	-	-	-
No of species observed	26	37	41	39	34	49	47	42	42	43	28	22	20	11

Relative abundances of major species and total species numbers in each lake. The symbol ### represents >10% relative abundance, ## represents 5–10%, # represents 2–5%, - represents <2%.

DISCUSSION

On Macquarie Island, as elsewhere in the sub-Antarctic region, araphid species (without a raphe slit on either valve face), especially *Fragilaria*, and monoraphid species (having a raphe slit on one valve face), especially *Achnanthes* and the genera formerly within *Achnanthes* formed major, sometimes dominant members of the lake diatom communities. Van de Vijver & Beyens (1999) consider a number of species (revised names in parentheses) to be confined to the sub-Antarctic zone: *Achnanthes confusa* (*Psammothidium confusum*), *A. germainii* (*Ps. germainii*), *Diatomella hustedtii* (*D. balfouriana*), *Pinnularia microstauron* var. *elongata* (*Pi. subantarctica* var. *elongata*). These species are well represented on Macquarie Island, reinforcing the view that a characteristic freshwater diatom flora exists in the sub-Antarctic, even though confined to small islands separated by long ocean distances. Saunders *et al.* (2008) identified 208 diatom species from 34 genera in samples from 50 ponds and lakes on Macquarie Island, compared to 102 species from 34 genera identified in the present study. The larger number of samples examined by Saunders *et al.* (2008) could be expected to reveal more species. If sampling had included soils and bogs a higher number of species would be expected in both studies. For example, an endemic species, *Gomphonema isabellae*, was later identified from a mire adjoining Green Gorge Tarn (Van de Vijver & McBride 2006) but was not observed in the samples forming the basis of this paper. It is difficult to comment on the higher number of species reported by Saunders *et al.* (2008) without seeing the full species list on which the number is based. On Île de la Possession (Crozet Archipelago) Van de Vijver & Beyens (1999) identified 210 diatom taxa from 127 lake and stream samples. The most abundant genera were *Fragilaria*, *Achnanthes* and *Navicula*, the same genera found on Macquarie Island (including the revised genera formerly within *Achnanthes* and *Navicula*). The higher species diversity on Île de la Possession may be explained by the greater habitat diversity, notably pH values ranging from 4.9 to 10, compared with values from 6.4 to 9.7 in the 14 Macquarie Island lakes examined in this study. Saunders *et al.* (2008) found a broader pH range of 5.5–9.95 by sampling 50 Macquarie Island lakes.

Some species, such as *Achnanthes clevei*, *Amphora coffeaeformis*, and *Cocconeis placentula*, are present or abundant on Macquarie Island but apparently absent from Kerguelen or Crozet islands. Only one species, *Fragilaria pulchella*, was observed in every lake. Four species were observed only in plateau lakes: *Brachysira exilis*, *Psammothidium therezienii*, *Lecohuia geniculata*, *Aulacoseira distans*, while one species, *Planothidium deliculatum*, was observed only in coastal terrace lakes. The diatom communities in the nine plateau lakes were generally more diverse with an average of 40 species, compared with the five coastal terrace lakes with an average of 24 species. The community of "S" Pond was distinct in having the centric species, *Aulacoseira distans*, as a major component. Its outlier status in the ordination matches its physical situation as a small, shallow and peat-based water body located at 220 m on the plateau. The other lakes at elevations about 200 m are large type "c" lakes. *Psammothidium confusum*, *Ps. confusum* var. *atomoides* and *Fragilaria capucina* var. *gracilis* typify the plateau lake communities. *Planothidium lanceolatum*, *Pl. quadripunctatum* and *F. pulchella* typify the coastal terrace lake communities (table 2). Two of the *F. capucina* morphotypes proposed by Van de Vijver *et al.* (2002)

appear to have different habitat preferences: the slender form, *F. vaucheriae* var. *gracilis* (formerly *F. vaucheriae* var. *longissima*), is abundant only in type "c" plateau lakes whereas *F. vaucheriae* var. *vaucheriae*, while present in the plateau lakes, is abundant mostly in type "a" coastal terrace lakes. *Planothidium deliculatum* was abundant only in the two lakes, Duck Lagoon and Langdon Point Pond, which had the highest conductivities. *Brachysira exilis* appears confined to the plateau lakes. *Eunotia curvata* was abundant in Pyramid Lake, which had the lowest pH.

There is broad agreement in the number of species observed in this study (shown in parentheses) with the number of species observed by Evans (1970) who listed a total of 84 (102) species in five ponds and lakes, 41 (34) species in Prion Lake, 25 (26) species in "S" Pond, and 37 (43) species in Duck Lagoon. The study by Bunt (1954) examined terrestrial diatoms and is not directly comparable. Comparison between environmental variables and lake position on Decorana Axis 1 (table 3) suggests the lake diatom communities are influenced to some extent by silica concentrations and by conductivity and pH. Silica concentrations are lowest in the plateau lakes and increase in a clear pattern along the axis to the coastal lakes suggesting a strong effect on the diatom communities. Conductivity also generally increases along the axis. The pattern of pH along the axis shown is less clear and shows highest values near the centre suggesting pH has less influence than silica concentrations and conductivity. Saunders *et al.* (2008), using a larger data set, found conductivity, pH and silicate concentrations made independent, significant contributions to explaining variation in the species data.

For most lakes, nitrate concentrations were below the detection limit, limiting the discrimination available. Within the group of similar coastal terrace lakes, Duck Lagoon and Brothers Lake were below detection limits while Langdon Point Pond was over 60 times the detection limit, suggesting nitrate concentrations were not a strong factor. A further consideration is that the values shown in table 3 are a "snapshot" and represent lake water quality at one point in time or the average of a limited number of readings. Water conductivity and nitrate concentrations in coastal terrace lakes are highly variable due to seawater ingress during storms and seasonal inputs from seal wallows and penguin rookeries (Evans 1970).

The environmental gradient corresponding to the order of lake communities along Axis 1 (table 3) seems to be related to lake elevation. There is a clear progression from the type "c" plateau lakes with elevations over 140 m asl through the type "b" plateau lakes (75–99 m asl) to the type "a" coastal terrace lakes. The environmental gradient linked to elevation that is influencing the communities could be temperature, a parallel situation to the terrestrial vegetation on Macquarie Island which shows marked altitude zonation. Based on thermograph data, Evans (1970) reports temperatures in Duck Lagoon on the coastal terrace were consistently several degrees higher than those for Prion Lake or "S" Pond on the plateau. This difference may be sufficient to affect the structure of the diatom communities in lakes at different elevations.

In addition to temperature, elevation affects the inputs of nutrients and ions from sea spray, which decrease with distance from the west coast due to the prevailing westerly weather patterns (Saunders *et al.* (2008)). The resultant changes in water chemistry could also produce an elevation-related pattern in lake diatom communities.

TABLE 3
Lake water quality and elevation

	'S' Pond	Pyramid Lake	Tulloch Lake	Lake Ainsworth	Prion Lake	Major Lake	Skua lake	Ifould Lake	Square Lake	Duck Lagoon	Brothers Lake	Green Gorge Tarn	Langdon Point Pond	Handspike Tarn
pH measured Oct/Nov1988		6.3		6.5		7.1	7.5		9.6	7.9	9.1	7.5		7.0
pH measured Nov/Dec 1989	7.3			7.2	7.2	7.4	8.1	8.0	9.9	9.7	8.4	8.2	7.1	7.1
pH measured Dec 1990		6.5	6.7		7.6	7.5			9.5	8.1		7.6		
pH measured Dec 1992			6.6						9.6	9.0				
Average pH	7.3	6.4	6.7	6.9	7.4	7.3	7.8	8.0	9.7	8.7	8.8	7.8	7.1	7.1
Conductivity (μ S/cm) measured Oct/Nov 1988		140		200		240	270		300	850	250	230		610
Conductivity (μ S/cm) measured Nov/Dec 1989	360			210	170	270	285	190	305	960	250	240	1240	740
Conductivity (μ S/cm) measured Dec 1990		98	121		92	169			212	1020	161	148		
Conductivity (μ S/cm) measured Dec 1992			150						280	810				
Average Conductivity	360	119	136	205	131	226	278	190	274	910	220	206	1240	675
Silicate (mg/L) measured Oct/Nov1988		0.75		0.10		0.22	2.2		0.15	1.3	9.8	7.5		3.5
Silicate (mg/L) measured Nov/Dec1989	0.16			0.12	0.16	0.22	0.39	6.5	0.37	0.55	12	4.9	1.8	4.3
Nitrate (mgN/L)	<0.042	n.d.	n.d.	<0.042	<0.042	<0.042	<0.042	<0.042	<0.042	<0.042	<0.042	0.11	2.66	0.56
Altitude (m)	220	200	190	240	160	200	140	220	99	5	75	10	5	5

Water pH and conductivity were measured in the field using portable meters (ICI Stick pH meter and Hanna HI 8633 portable conductivity meter). Silicate concentrations were determined at Macquarie Island Base by colourimetric analysis (Hach model DREL/1C Direct-Reading Environmental Laboratory). Nitrate concentrations were determined by the Australian Government Analytical Laboratories (Kingston, Tasmania) in lake water samples transported in prepared plastic bottles. The value of 0.042 mgN/L was the detection limit for nitrate. nd = no data.

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APPENDIX 1

Order of samples in list follows Twinspan ordination based on relative abundance of diatom species in each sample without transformation and including all species

Lake	Date of collection	Particulars of sample
"S" Pond	29 Nov 1990	Brown slime at southeast margin in 20 cm depth
"S" Pond	19 Dec 1991	Algae and submerged moss at east edge in 10 cm
"S" Pond	29 Feb 1992	Myriophyllum tips at east edge in 10 cm
"S" Pond	02 Dec 1989	Filamentous algae and gelatinous mud in 10 cm depth at north edge
"S" Pond	01 Dec 1989	Filamentous algae and moss in 10 cm depth at south edge
Prion Lake	26 Nov 1990	Submerged moss at northeast corner in 20 cm depth
Pyramid Lake	17 Mar 1992	Rock scrapings at east edge in 10 cm depth
Prion Lake	31 Jan 1992	Algae and submerged moss from rocks
Lake Ainsworth	10 Nov 1988	Rock scrapings at west margin near skua club
Lake Ainsworth	08 Mar 1993	Rock scrapings at southwest edge in 25 cm, 1 m from shore
Lake Ainsworth	06 Dec 1989	Moss at south margin 3 m from shore in 50 cm depth
Lake Ainsworth	06 Dec 1989	Rock scrapings at south margin near southwest corner in 20 cm depth
Lake Ainsworth	06 Dec 1989	Rock scrapings at east margin near northeast corner in 20 cm
Lake Ainsworth	06 Dec 1989	Submerged moss at east margin near northeast corner in 20 cm
Lake Ainsworth	06 Dec 1989	Submerged moss at east margin near northeast corner in 20 cm
Pyramid Lake:	17 Mar 1992	Submerged moss from rocks at edge
Prion Lake	01 Mar 1991	Rock scrapings at northern edge
Prion Lake	21 Dec 1989	Submerged moss at northern margin in 20 cm depth
Prion Lake	13 Jan 1992	Submerged vegetation
Tulloch Lake	26 Nov 1990	Submerged moss at northwest margin in 30 cm depth
Tulloch Lake	26 Nov 1990	Rock scrapings at northwest margin in 30 cm depth
Lake Ainsworth	10 Nov 1988	Rock scrapings at southeast corner remote from skua club
Pyramid Lake	08 Nov 1988	Submerged bryophyte <i>Ditrichum strictum</i>
Pyramid Lake	08 Nov 1988	Rock scrapings
Pyramid Lake	27 Nov 1990	Submerged moss at northwest edge in 20 cm depth
Tulloch Lake	31 Oct 1988	Submerged moss at 30 cm depth at eastern edge
Tulloch Lake	02 Mar 1992	Submerged moss and algae at west shore
Tulloch Lake	10 Dec 1992	Submerged moss at northwest corner in 20 cm depth
Tulloch Lake	10 Dec 1992	Rock scrapings at northwest corner in 20 cm depth
Tulloch Lake	20 Mar 1993	<i>Myriophyllum</i> at southern end 150 m east of outlet in 50 cm depth
Tulloch Lake	20 Mar 1993	Rock scrapings at southern end 150 m east of outlet in 50 cm depth
Tulloch Lake	31 Oct 1988	Rock scrapings at 20 cm depth at eastern edge
Tulloch Lake	31 Jan 1992	Submerged moss and algae at western edge in 20 cm depth

Appendix 1 cont.

Lake	Date of collection	Particulars of sample
Major Lake	08 Nov 1988	Submerged bryophyte <i>Ditrichum strictum</i> in 10 cm depth
Major Lake	23 Nov 1988	Rock scrapings at site without bird use and 50 m west of skua club
Major Lake	10 Mar 1993	<i>Myriophyllum</i> in 30 cm depth 1.5 m from shore
Major Lake	10 Mar 1993	Rock scrapings in 30 cm depth 1.5 m from shore
Major Lake	11 Dec 1989	Rock scrapings at water sampling site in 30 cm depth
Major Lake	11 Dec 1989	Rock scrapings at western margin near outlet in 30 cm depth
Major Lake	11 Dec 1989	Rock scrapings at western margin near outlet in 30 cm depth repeat digestion
Major Lake	27 Nov 1990	Rock scrapings with moss and algae at western margin in 20 cm depth
Major Lake	23 Nov 1988	Rock scrapings from southwest corner near? Skua club
Skua Lake	01 Nov 1988	<i>Myriophyllum</i> from edge 200 m east of water sampling site
Skua Lake	14 Dec 1989	<i>Myriophyllum</i> at shoreline near water sampling site in 30 cm depth
Skua Lake	14 Dec 1989	Rock scrapings near water sampling site at shoreline in 20 cm depth
Skua Lake	14 Dec 1989	<i>Myriophyllum</i> at shoreline near outlet in 30 cm depth
Skua Lake	01 Nov 1988	Rock scrapings from edge 200 m east of water sampling site
Skua Lake	01 Nov 1988	<i>Myriophyllum</i> near water sampling site at western end of south margin
Skua Lake	01 Nov 1988	Rock scrapings near water sampling site at western end of south margin
Ifould Lake	13 Dec-1989	Submerged moss at eastern edge near outlet in 20 cm depth
Ifould Lake	13 Dec 1989	Rock scrapings at western margin near outlet in 10 cm depth
Green Gorge Tarn	11 Mar 1993	<i>Myriophyllum</i> in 20 cm depth
Ifould Lake	13 Dec 1989	<i>Myriophyllum</i> at southeast margin on shore
Square Lake	10 Dec 1992	Rock scrapings at eastern end of northern edge in 15 cm depth
Square Lake	10 Dec- 992	<i>Myriophyllum</i> at eastern end of northern edge in 15 cm depth
Square Lake	10 Dec 1992	Rock scrapings at east end of northern edge in 15 cm depth
Square Lake	10 Dec 1992	<i>Myriophyllum</i> at east end of northern edge in 15 cm depth
Square Lake	26 Nov 1990	<i>Myriophyllum</i> at surface at southeast corner
Square Lake	26 Nov 1990	Rock scrapings at southeast corner in 30 cm depth
Square Lake	01 Mar 1991	<i>Myriophyllum</i> at northeast edge.
Green Gorge Tarn	04 Nov 1988	<i>Myriophyllum</i> at middle of southeast edge
Green Gorge Tarn	14 Dec 1989	<i>Myriophyllum</i> east end of northern margin on surface
Green Gorge Tarn	28 Nov 1990	<i>Myriophyllum</i> at surface at eastern margin
Brothers Lake	31 Jan 1992	<i>Myriophyllum</i> at northern edge in 20 cm depth
Green Gorge Tarn	30 Nov 1991	<i>Myriophyllum</i>
Square Lake	01 Mar 1991	Rock scrapings at northeast edge
Brothers Lake	03 Nov 1988	<i>Myriophyllum</i> and algae at northeast edge
Brothers Lake	03 Nov 1988	<i>Myriophyllum</i> at northern margin near northeast corner
Brothers Lake	03 Nov 1988	Rock scrapings from mid northern margin
Brothers Lake	28 Nov 1990	<i>Myriophyllum</i> at surface at eastern margin
Brothers Lake	17 Dec 1991	Floating algae and submerged moss at northern edge in 20 cm depth
Brothers Lake	16 Mar 1992	<i>Myriophyllum</i> at northern edge in 20 cm depth
Brothers Lake	21 Dec 1989	Rock scrapings at northern margin in 30 cm depth
Brothers Lake	21 Dec 1989	<i>Myriophyllum</i> at northern margin in 50 cm depth and 2 m from edge
Brothers Lake	21 Dec 1989	<i>Myriophyllum</i> at surface near water sampling site
Brothers Lake	28 Nov 1990	Rock scrapings at northwest margin in 20 cm depth
Duck Lagoon	13 Nov 1988	Rock scrapings from eastern edge
Duck Lagoon	26 Nov 1990	Rock scrapings at northern site in 50 cm depth
Duck Lagoon	01 Dec 1989	Bottom detritus at southeastern margin 2 m from edge in 50 cm depth
Duck Lagoon	01 Dec 1989	Filamentous algae in about 30 cm depth and 2 m from edge of southeastern margin
Duck Lagoon	26 Nov 1990	<i>Myriophyllum</i> at surface at southern site
Duck Lagoon	28 Feb 1991	Floating vegetation at northern edge
Duck Lagoon	22 Dec 1989	<i>Myriophyllum</i> at southwest shore on surface
Duck Lagoon	22 Dec 1989	<i>Myriophyllum</i> at northeast shore on surface
Duck Lagoon	22 Dec 1989	<i>Myriophyllum</i> at eastern shore on surface
Duck Lagoon	22 Dec 1989	<i>Myriophyllum</i> at northwestern shore 3 m from at edge in 80 cm depth
Duck Lagoon	01 Dec 1989	Rock scrapings from 30 cm depth near at northern shore
Duck Lagoon	26 Nov 1990	Rock scrapings at southern site in 50 cm depth

Appendix 1 cont.

Lake	Date of collection	Particulars of sample
Duck Lagoon	02 Feb 1991	Rock scrapings at southern bank.
Duck Lagoon	22 Dec 1989	Sediment at northeastern margin near edge in 30 cm depth
Duck Lagoon	26 Nov 1990	Bottom detritus in 30 cm depth
Handspike Pond	27 Nov 1989	Marginal vegetation in about 10 cm depth at southwestern edge
Handspike Pond	27 Nov 1989	Fibrous mud at edge in 30 cm depth
Langdon Point Pond	26 Dec 1989	Peat scrapings at western margin in 20 cm depth
Langdon Point Pond	26 Dec 1989	Rock scrapings in 40 cm depth near eastern shore

APPENDIX 2

Diatom species observed in Macquarie Island lakes and ponds

<i>Achnanthes clevei</i> Grunow	<i>Navicula rhyncocephala</i> Kützing
<i>Achnanthes inflata</i> Kützing	<i>Navicula subrhyncocephala</i> Hustedt
<i>Achnanthes lapponica</i> var. <i>ninkei</i> (Guermeur & Manguin) Reimer	<i>Naviculadicta elorantana</i> Lange-Bertalot
<i>Achnanthes linearis</i> W. Smith	<i>Naviculadicta seminulum</i> Grunow
<i>Achnanthidium minutissimum</i> (Kützing) Czarnecki	<i>Neidium affine</i> Ehrenberg
<i>Achnanthidium modestiforme</i> (Lange-Bertalot) Van de Vijver	<i>Neidium iridis</i> (Ehrenberg) Cleve
<i>Adlafia bryophila</i> (Petersen) Lange-Bertalot	<i>Nitzschia</i> aff. <i>linearis</i> (Agardh) W. Smith
<i>Amphora coffeaeformis</i> Agardh	<i>Nitzschia dissipata</i> (Kützing) Grunow
<i>Amphora copulata</i> (Kützing) Schoeman & Archibald	<i>Nitzschia frustulum</i> (Kützing) Grunow
<i>Amphora veneta</i> Kützing	<i>Nitzschia gracilis</i> Hantzsch
<i>Aulacoseira distans</i> (Ehrenberg) Simonsen	<i>Nitzschia inconspicua</i> Grunow
<i>Brachysira exilis</i> (Kützing) Round & Mann	<i>Nitzschia vermicularis</i> (Kützing) Grunow
<i>Caloneis bacillum</i> (Grunow) Mereschkowsky	<i>Nupela chilensis</i> (Krasske) Lange-Bertalot
<i>Caloneis marnieri</i> Manguin	<i>Pinnularia acorica</i> Hustedt
<i>Cocconeis neothumensis</i> Krammer	<i>Pinnularia acidicola</i> var. <i>elongata</i> Van de Vijver & Le Cohu
<i>Cocconeis placentula</i> Ehrenberg	<i>Pinnularia appendicula</i> (Agardh) Cleve
<i>Cymbella gracilis</i> (Rabhenhorst) Cleve	<i>Pinnularia borealis</i> var. <i>scalaris</i> (Ehrenberg) Rabenhorst
<i>Cymbella microcephala</i> Grunow	<i>Pinnularia gibba</i> Ehrenberg
<i>Diademesmis arcuata</i> (Heiden) Lange-Bertalot	<i>Pinnularia lata</i> Brébisson
<i>Diademesmis subantarctica</i> Le Cohu & Van de Vijver	<i>Pinnularia microstauron</i> (Ehrenberg) Cleve
<i>Diatomella balfouriana</i> Greville	<i>Pinnularia obscura</i> Krasske
<i>Diploneis subovalis</i> Cleve	<i>Pinnularia subantarctica</i> var. <i>elongata</i> (Manguin) Van de Vijver & Le Cohu
<i>Encyonema vulgare</i> Krammer	<i>Pinnularia viridis</i> Nitzschia
<i>Eolimna minima</i> (Grunow) Lange-Bertalot	<i>Planothidium aueri</i> (Krasske) Lange-Bertalot
<i>Eunotia</i> aff. <i>subarcuatoides</i> Alles, Nörpel & Lange-Bertalot	<i>Planothidium cyclophorum</i> (Heiden) Van de Vijver
<i>Eunotia curvata</i> (Kützing) Lagerstedt	<i>Planothidium deliculatum</i> (Kützing) Round & Bukthiyarova
<i>Eunotia paludosa</i> Grunow	<i>Planothidium lanceolatum</i> (Brébisson) Lange-Bertalot
<i>Fragilaria capucina</i> var. <i>gracilis</i> (Kützing) Lange-Bertalot	<i>Planothidium quadripunctatum</i> (Oppenheim) Sabbe
<i>Fragilaria capucina</i> var. <i>rumpens</i> (Oestrup) Hustedt	<i>Psammothidium abundans</i> (Manguin) Bukthiyarova & Round
<i>Fragilaria capucina</i> var. <i>vaucheriae</i> (Kützing) Lange-Bertalot	<i>Psammothidium confusum</i> (Manguin) Van de Vijver
<i>Fragilaria exigua</i> Grunow	<i>Psammothidium confusum</i> var. <i>atomoides</i> (Manguin) Van de Vijver
<i>Fragilaria pulchella</i> (Ralfs) Lange-Bertalot	
<i>Frustulia rhomboides</i> (Ehrenberg) de Toni	
<i>Frustulia subantarctica</i> Van de Vijver & Beyens nov. spec.	
<i>Geissleria paludosa</i> (Hustedt) Lange-Bertalot	<i>Psammothidium germainii</i> (Manguin) Sabbe
<i>Gomphonema affine</i> Kützing	<i>Psammothidium incognitum</i> Van de Vijver
<i>Gomphonema intricatum</i> Kützing	<i>Psammothidium manguinii</i> (Hustedt) Van de Vijver
<i>Gomphonema stonei</i> Reichardt	<i>Psammothidium oblongellum</i> (Oestrup) Van de Vijver
<i>Gomphonema subantarctica</i> Van de Vijver & Beyens nov. spec.	<i>Psammothidium stauroneioides</i> (Manguin) Bukthiyarova
<i>Gomphonema tumidum</i> (Skvortzov & Meyer) Lange-Bertalot & Reichardt	<i>Psammothidium therezienii</i> (Le Cohu & Maillard) Van de Vijver
<i>Lecohuia geniculata</i> (Germain) Lange-Bertalot	<i>Stauroforma exiguiiformis</i> (Lange-Bertalot) Flower, Jones & Round
<i>Luticola mutica</i> (Kützing) Mann	
<i>Mastogloia recta</i> Hustedt	<i>Stauroneis anceps</i> Ehrenberg
<i>Navicula cincta</i> (Ehrenberg) Kützing	<i>Stauroneis gracilior</i> (Ehrenberg) Reichardt
<i>Navicula cincta</i> var. <i>heuslerii</i> (Grunow) Grunow	<i>Stauroneis kriegeri</i> Patrick
<i>Navicula gregaria</i> Donkin	<i>Stauroneis phoenicenteron</i> Ehrenberg
<i>Navicula hustedtii</i> Krasske	<i>Staurosira alpestris</i> (Krasske ex Hustedt) Van de Vijver
<i>Navicula lanceolata</i> (Agardh) Ehrenberg	<i>Staurosira circula</i> Van de Vijver & Beyens
<i>Navicula muticopsis</i> Van Heurck	<i>Staurosira jolinae</i> Van de Vijver
<i>Navicula pseudocitris</i> Manguin	<i>Staurosira leptostauron</i> Ehrenberg
<i>Navicula pseudoscutiformis</i> Hustedt	<i>Staurosira pinnata</i> Ehrenberg
<i>Navicula pupula</i> Kützing	<i>Surirella angusta</i> var. <i>constricta</i> Hustedt
	<i>Surirella linearis</i> W. Smith
	<i>Surirella ovata</i> Kützing

APPENDIX 3

Pooled relative abundances of all taxa in each lake

	S' Pond	Pyramid Lake	Tullock Lake	Lake Anasawth	Iron Lake	Major Lake	Star Lake	Hood Lake	Spartan Lake	Duck Lake	Brothers Lake	Great George Lake	Landon Pond	Husky Lake
<i>Achnanthes clevei</i>	-	-	-	-	-	6.84%	-	10.29%	6.78%	0.04%	-	-	-	-
<i>Achnanthes inflata</i>	-	-	-	-	-	-	0.09%	0.21%	0.14%	0.26%	-	-	-	-
<i>Achnanthes lapponica</i> var. <i>ninkel</i>	0.13%	0.07%	0.07%	0.16%	0.46%	-	0.09%	-	-	-	0.11%	-	-	-
<i>Achnanthes linearis</i>	-	-	-	-	-	-	0.32%	-	-	-	0.12%	0.46%	-	-
<i>Achnanthidium minutissimum</i>	0.13%	0.50%	0.72%	1.94%	1.56%	15.30%	6.45%	12.24%	4.68%	0.04%	-	0.46%	-	-
<i>Achnanthidium modestiforme</i>	-	-	0.04%	-	-	2.87%	0.83%	0.72%	-	-	-	0.11%	-	-
<i>Adafia bryophila</i>	1.03%	0.64%	0.22%	1.21%	1.24%	0.07%	-	-	-	-	-	-	-	-
<i>Amphora coffeaeformis</i>	-	-	0.07%	-	0.33%	1.71%	3.18%	1.85%	19.61%	-	0.06%	0.11%	-	-
<i>Amphora copulata</i>	-	-	-	-	-	-	-	-	0.03%	-	-	-	-	-
<i>Amphora veneta</i>	-	-	-	-	-	-	-	-	0.03%	-	-	-	-	-
<i>Aulacoseira distans</i>	15.94%	1.35%	0.69%	-	-	-	0.28%	0.21%	-	-	-	-	-	-
<i>Brachysira exilis</i>	37.16%	2.41%	20.49%	18.62%	3.46%	2.81%	1.01%	-	0.03%	-	-	-	-	-
<i>Caloneis bacillum</i>	0.06%	0.50%	0.14%	0.16%	0.13%	-	0.18%	-	0.03%	-	-	-	-	-
<i>Caloneis marnieri</i>	-	-	-	-	-	-	0.05%	0.10%	-	-	-	-	-	-
<i>Cocconeis neothumensis</i>	-	-	-	-	-	-	-	0.07%	-	-	-	-	-	-
<i>Cocconeis placentula</i>	-	-	0.07%	-	-	1.03%	0.78%	7.30%	8.68%	10.21%	6.16%	7.90%	-	-
<i>Cymbella gracilis</i>	-	0.28%	1.48%	4.05%	0.65%	3.35%	0.37%	-	-	-	-	-	-	-
<i>Cymbella microcephala</i>	-	-	-	-	0.39%	3.35%	4.51%	7.82%	4.75%	-	0.12%	-	-	-
<i>Diademesis arcuata</i> (Heiden)	-	0.07%	-	-	0.07%	-	-	-	-	0.04%	-	-	-	-
<i>Diademesis subantarctica</i>	-	-	-	-	-	-	-	-	-	1.67%	-	-	-	-
<i>Diatomella balfouriana</i>	-	0.14%	0.79%	-	-	2.53%	6.17%	7.92%	-	-	-	-	-	-
<i>Diploneis subovalis</i>	-	-	-	-	-	0.07%	-	-	0.03%	-	-	-	-	-
<i>Encyonema vulgare</i>	-	-	-	-	-	-	-	-	0.07%	-	-	-	-	-
<i>Eolimna minima</i>	-	-	-	-	-	-	-	0.10%	0.03%	0.39%	2.01%	0.11%	-	-
<i>Eunotia aff. subarcuatoides</i>	-	0.07%	-	-	-	-	-	-	-	-	-	-	-	-
<i>Eunotia curvata</i>	-	42.56%	0.11%	1.46%	2.93%	-	-	-	0.03%	-	0.12%	-	-	0.16%
<i>Eunotia paludosa</i>	-	-	0.07%	0.08%	0.33%	-	-	-	-	-	-	-	-	-
<i>Fragilaria capucina</i> var. <i>gracilis</i>	1.61%	14.38%	15.33%	38.38%	44.33%	31.90%	30.20%	3.19%	1.63%	-	-	-	-	-
<i>Fragilaria capucina</i> var. <i>rumpens</i>	-	-	-	5.10%	-	0.14%	-	-	-	0.13%	-	-	-	-
<i>Fragilaria capucina</i> var. <i>vaucheriae</i>	0.26%	0.07%	0.58%	4.37%	-	5.41%	6.58%	3.50%	16.08%	6.87%	2.61%	1.95%	5.31%	-
<i>Fragilaria exigua</i>	-	-	-	0.08%	-	-	-	-	0.10%	28.97%	-	-	4.99%	-
<i>Fragilaria pulchella</i>	0.19%	0.92%	0.14%	0.16%	0.20%	6.71%	0.92%	12.86%	14.89%	5.54%	48.14%	66.78%	0.97%	28.73%
<i>Frustulia rhomboides</i>	1.87%	0.07%	0.04%	-	-	0.07%	0.05%	-	-	-	-	-	-	-
<i>Frustulia subantarctica</i>	-	-	-	-	-	-	-	0.10%	-	-	-	-	-	-
<i>Gelssleria paludosa</i>	-	-	-	-	0.39%	0.07%	-	-	0.07%	0.47%	0.12%	0.34%	0.64%	-
<i>Gomphonema affine</i>	-	-	-	0.81%	0.46%	0.07%	-	-	3.02%	0.09%	17.05%	0.46%	1.45%	-
<i>Gomphonema intricatum</i>	-	0.21%	0.72%	0.49%	0.65%	0.75%	2.03%	-	0.24%	0.04%	0.18%	-	-	-
<i>Gomphonema stonei</i>	-	0.85%	0.43%	0.08%	0.59%	0.21%	-	1.23%	5.36%	0.77%	-	1.60%	-	1.41%
<i>Gomphonema subantarctica</i>	-	-	-	-	0.07%	-	-	0.41%	-	-	-	-	-	-
<i>Gomphonema tumidum</i>	-	-	-	-	-	-	-	0.10%	-	-	0.06%	0.11%	-	-
<i>Lecothia geniculata</i>	0.19%	0.78%	0.83%	0.16%	8.28%	0.41%	0.51%	0.41%	-	-	-	-	-	-
<i>Luticola mutica</i>	-	-	-	-	-	-	-	-	0.04%	-	-	-	-	-
<i>Mastogloia recta</i>	-	-	-	-	-	0.07%	-	-	-	-	-	-	-	-
<i>Navicula cincta</i>	-	-	0.07%	0.16%	-	0.21%	-	-	-	-	-	-	-	-
<i>Navicula cincta</i> var. <i>heufferli</i>	-	-	-	-	-	-	0.09%	-	-	-	-	-	-	-
<i>Navicula gregaria</i>	-	-	-	0.32%	-	0.07%	-	-	0.04%	-	-	-	-	-
<i>Navicula hustedii</i>	-	-	-	-	-	-	-	-	0.09%	-	-	-	-	-
<i>Navicula lanceolata</i>	-	-	-	-	-	-	-	-	-	0.06%	-	1.29%	-	-
<i>Navicula muticopsis</i>	-	-	0.07%	-	-	-	-	-	-	-	-	-	-	-
<i>Navicula pseudocitris</i>	-	-	-	-	-	-	0.09%	-	-	0.17%	0.41%	-	-	-
<i>Navicula pseudoscutiformis</i>	-	0.14%	0.14%	-	0.33%	1.44%	2.30%	0.62%	-	0.17%	-	-	0.81%	-
<i>Navicula pupula</i>	-	0.21%	-	0.16%	0.39%	-	0.05%	-	-	0.09%	0.06%	-	-	-
<i>Navicula rhyncocephala</i>	0.06%	1.77%	1.62%	1.94%	0.33%	0.27%	0.18%	0.21%	-	0.20%	-	-	-	-
<i>Navicula subrhyncocephala</i>	-	-	-	-	-	-	-	-	0.20%	0.82%	-	-	-	-
<i>Naviculadicta elorantana</i>	1.29%	-	-	0.08%	0.13%	0.14%	0.18%	-	0.03%	0.09%	-	1.13%	2.51%	-
<i>Naviculadicta seminulum</i>	1.03%	1.13%	0.90%	0.24%	2.87%	0.89%	1.01%	0.41%	0.07%	1.89%	1.07%	6.76%	2.98%	-
<i>Neidium affine</i>	-	-	-	-	-	-	-	-	-	-	0.11%	-	-	-
<i>Neidium iridis</i>	-	0.07%	0.40%	-	-	0.07%	-	-	-	-	-	-	-	-
<i>Nitzschia aff. linearis</i>	-	0.07%	0.25%	2.35%	0.07%	1.03%	0.87%	0.10%	2.31%	-	1.66%	-	-	-
<i>Nitzschia dissipata</i>	-	-	-	-	-	0.62%	0.05%	0.10%	0.07%	0.60%	-	-	-	-
<i>Nitzschia frustulum</i>	0.90%	2.20%	1.08%	0.08%	0.98%	2.19%	1.06%	0.93%	0.78%	-	-	-	-	-
<i>Nitzschia gracilis</i>	0.26%	0.35%	-	0.08%	-	0.07%	-	-	12.21%	3.09%	7.70%	-	-	-
<i>Nitzschia inconspicua</i>	-	-	-	0.08%	-	-	-	-	0.88%	1.67%	1.07%	-	-	-
<i>Nitzschia vermicularis</i>	-	-	-	-	-	-	-	-	0.03%	-	-	-	-	-
<i>Nupela chilensis</i>	-	-	-	-	-	-	-	-	0.17%	-	-	-	-	-
<i>Pinnularia acoricola</i>	0.06%	0.14%	-	0.49%	0.07%	-	-	-	-	-	-	0.16%	-	-
<i>Pinnularia acidicola</i> var. <i>elongata</i>	-	-	-	-	-	-	0.10%	-	-	-	-	-	-	-
<i>Pinnularia appendicula</i>	-	-	-	-	-	-	0.72%	-	0.30%	-	-	-	-	-
<i>Pinnularia borealis</i> var. <i>scalaris</i>	-	0.07%	-	-	-	-	0.10%	-	-	-	-	-	-	-
<i>Pinnularia gibba</i>	0.13%	-	0.18%	-	0.07%	-	-	-	-	0.04%	-	-	-	-
<i>Pinnularia lata</i>	-	0.04%	-	-	-	-	-	-	-	-	-	-	-	-
<i>Pinnularia microstauron</i>	0.45%	-	-	-	-	0.05%	0.21%	-	0.04%	-	-	0.16%	0.16%	-
<i>Pinnularia obscura</i>	0.39%	-	0.07%	-	-	-	-	-	-	-	-	-	-	-
<i>Pinnularia subantarctica</i> var. <i>elongata</i>	-	0.07%	-	0.16%	0.07%	-	-	-	0.04%	-	-	-	-	-
<i>Pinnularia viridis</i>	-	-	-	0.24%	0.20%	0.07%	-	-	0.03%	-	-	-	-	-
<i>Planothidium aueri</i>	0.06%	0.35%	0.07%	-	1.30%	1.10%	0.74%	9.36%	-	-	0.23%	-	-	-
<i>Planothidium cyclophorum</i>	-	-	-	-	-	-	0.05%	0.21%	0.34%	-	0.12%	-	-	-
<i>Planothidium deliculatum</i>	-	-	-	-	-	-	-	0.24%	8.45%	-	-	19.00%	0.63%	-
<i>Planothidium lanceolatum</i>	-	-	-	0.08%	-	0.27%	0.37%	0.51%	7.55%	2.53%	3.91%	13.75%	15.14%	10.68%
<i>Planothidium quadrupunctatum</i>	-	-	0.47%	0.89%	0.13%	0.96%	1.01%	0.41%	1.53%	12.40%	0.06%	3.44%	31.72%	49.45%
<i>Psammothidium abundans</i>	18.58%	0.50%	10.43%	1.21%	0.91%	2.87%	13.12%	1.54%	0.14%	0.04%	0.06%	0.11%	-	-
<i>Psammothidium confusum</i>	1.42%	7.86%	15.04%	6.96%	17.93%	3.15%	0.23%	20.68%	0.20%	-	0.24%	0.11%	0.64%	-
<i>Psammothidium confusum</i> var. <i>atomoides</i>	-	17.35%	25.32%	3.72%	6.39%	2.67%	0.18%	2.16%	-	0.13%	0.71%	0.23%	1.13%	0.16%
<i>Psammothidium germainii</i>	-	-	-	0.08%	-	-	-	-	-	-	-	-	-	-
<i>Psammothidium incognitum</i>	1.03%	1.42%	0.22%	0.08%	0.52%	0.34%	0.09%	-	-	-	-	-	-	-
<i>Psammothidium manginii</i>	0.13%	0.42%	0.29%	1.54%	0.85%	0.34%	0.37%	0.10%	-	-	-	-	-	-
<i>Psammothidium oblongellum</i>	0.19%	-	0.04%	-	0.07%	0.07%	0.83%	-	-	0.04%	-	-	6.28%	-
<i>Psammothidium stauroneioides</i>	-	-	-	0.32%	-	-	-	0.10%	-	-	-	-	-	-
<i>Psammothidium therezienii</i>	15.42%	-	-	1.21%	0.07%	-	0.28%	0.21%	-	-	-	-	-	-
<i>Stauriforma exiguiiformis</i>	-	-	-	-	0.14%	0.14%	-	-	-	0.09%	0.06%	-	1.13%	-
<i>Stauronella anceps</i>	-	-	-	-	-	-	-	-	-	-	-	0.04%	-	-
<i>Stauronella gracillor</i>	-	-	-	-	-	-	0.10%	-	-	-	-	-	-	-
<i>Stauronella kriegeri</i>	-	-	-	-	-	-	-	-	0.04%	-	-	-	-	-
<i>Stauronella phoenicenteron</i>	-	-	0.04%	0.16%	-	0.05%	-	-	-	-	-	-	0.16%	-
<i>Stauronella alpestris</i>	-	-	0.07%	-	0.07%	1.06%	0.10%	-	0.30%	0.47%	1.37%	-	-	3.14%
<i>Stauronella circula</i>	-	-	-	-	-	-	-	0.24%	-	-	-	-	-	-
<i>Stauronella jollinae</i>	-	-	-	-	-	0.14%	0.87%	0.51%	2.10%	-	-	-	-	-
<i>Stauronella leptostauron</i>	-	-	-	-	-	-	0.09%	-	-	-	-	-	-	-
<i>Stauronella pinnata</i>	-	-	-	-	1.71%	9.99%	-	0.07%	9.06%	0.12%	-	1.13%	-	-
<i>Surirella angusta</i> var. <i>constricta</i>	-	-	-	-	-	-	-	0.03%	-	-	-	-	-	-
<i>Surirella linearis</i>	-	-	0.14%	-	0.07%	-	-	-	0.04%	-	-	-	-	-
<i>Surirella ovata</i>	-	-	-	-	-	-	-	0.10%	-	-	-	-	-	-

ANTARCTIC VIGNETTES III: SHACKLETON'S AB – WILLIAM FREDERICK WILLIAMS

by Herbert J. G. Dartnall

(with four plates)

Dartnall, H.J.G. 2009 (11:xii): Antarctic vignettes III: Shackleton's AB – William Frederick Williams. *Papers and Proceedings of the Royal Society of Tasmania* 143(2): 83–86. ISSN 0080-4703. Department of Biological Sciences, Macquarie University, New South Wales 2109, Australia. Email: herbdartnall@pip.com.au

William Frederick Williams was born in Tasmania in 1886. He joined Ernest Shackleton's British Antarctic Expedition, signing on in the name of W. Williams, and served as an AB (Able Seaman) on the Steam Yacht *Nimrod* on her second voyage south (1908–09). On return to Tasmania he tried his hand at a variety of jobs before settling in the Lakes district of Tasmania as the manager of guest houses catering for trout fishermen in the 1920s. He retired to Lorne, Victoria, and died in Melbourne in 1964 aged 77.

Key Words: William F. Williams, Able Seaman, S.Y. *Nimrod*, Shackleton's British Antarctic Expedition.

INTRODUCTION

Serendipity often plays a role in the discovery of information relating to projects undertaken and has played its part for some of the men from the early Antarctic expeditions whose stories are forming the basis of the Antarctic Vignettes series of papers. William Williams is not an uncommon name; indeed there are two men with that name who served on expeditions during the heroic age of Antarctic exploration – an Able Seaman with Shackleton's British Antarctic Expedition 1907–09 (BT 100/28, Crossley 1997, Riffenburgh 2004), and a Chief Engine Room Artificer with Captain Scott's British Antarctic Expedition 1910–13. The second William Williams was a Royal Navy man so his service papers are accessible at the National Archives, Kew, but the possibility of finding out anything about the first William Williams appeared remote. Indeed when my mother-in-law's next door neighbour told me that her late husband used to go fishing with the son of a man who had sailed with Shackleton I did not believe her. Fortunately, investigation of this contact proved fruitful and her claim was vindicated.

WILLIAM FREDERICK WILLIAMS

William Frederick Williams was born on 23 December 1886 at Scottsdale, Tasmania, the eldest son of Frederick William Williams and his wife Sarah Sheehan. Frederick (WFW's father) was a huge man, who despite having only one arm – his right arm had been severed in a chaff cutter when he was aged only nine – was a world champion axeman. He was often away and Sarah (WFW's mother), a nurse and midwife, was the main supporter of the family of ten children. Nothing is known about WFW's early life, but the family lived in Port Sorell, near Devonport, where most of the boys drifted into seafaring jobs when they left home.

ABOARD THE NIMROD

WFW was nearly 22 when he joined the S.Y. *Nimrod* at Lyttelton, New Zealand, on 24 November 1908 (pl. 1). He signed on as W. Williams and served throughout the second voyage taking his discharge when the ship returned

to Poplar, London, on 31 August 1909 (BT 100/28). He was fond of the ship but considered Ernest Shackleton, the expedition leader, cavalier about the *Nimrod*, which WFW called the *Thunderin' Ice Berg Chaser* in his diary. Amongst the personal items he took south were a jew's harp and a banjo. It is interesting to speculate whether WFW's prowess on the banjo was instrumental in Leonard Hussey's appointment as a banjo-playing meteorologist on Sir Ernest Shackleton's later Imperial Trans-Antarctic expedition, in 1914, and also that of Joseph Williams, the banjo-playing carpenter with Douglas Mawson's BANZAR Expedition in 1930–31. Whilst on the *Nimrod* WFW kept a small notebook/diary, in which



PLATE 1
William Frederick Williams.

he records the weather and notes the principal actions of his watch. This notebook also contains a brief summary of the voyage south (text and spelling as written):

It was on November 23 that I joined the Nimrod in Lyttelton N.Z. to go to the frozen South on the return trip to bring Lieut Shackleton back and his party that went to find the South Pole but did not have the luck to reach it but very near he discovered the Magnetic Pole but I am running away from my story we left Lyttelton on Dec 1st and a big crowd down to see us off we got under way at half past 3 amid deafening cheers from all man of wars crews as we were leaving the wharf the tug boat came down to the Heads with us & then left us to go on our own. We had fine weather we were three weeks going down to the ice pack which was in 67 degrees South it was a lovely sight the sun was shining all day and all night so we had no look out to keep all hands were up on the fore castle Head watching the progress we thought there was nothing like it but we soon go full up of seeing ice we had three months down there it was deadly we had to do some heavy work sledging when we got up to the hut where the Party where living we had some great fun catching seals and penguins and skying we never had the pleasure of being on them before we used to get some lovely spills off them. but we soon had to give them a spell when we could work. When we got up to the hut we were all excited to see living people and a house they were as pleased as we where so we gave them some fresh provisions and then went off to look for the two men that left the ship off Cape Bird for the Hut with the mail (Second Officer Aeneas MacIntosh and Able Seaman Michael Thomas McGillion) but we could not get to Cape Bird on account of the ice coming down on top of us and drove us to the Western Mountains, where we put in

ten days iced in. on the tenth day we forced our way out and made for the Hut we reached it with some difficulty and was pleased to find our two men where there or at least one. Mr. MacIntosh had gone with the supporting party for Shackleton. McGillion came on board and we were all glad to see him his face was all skinned where they had had a terrible time coming over the mountain they had a very heavy blizzard for two day they had no grub so they had a very hard time when they were seen they where sliding down the side of Mount Erebus they slid over 3000ft so one of the shore party seen them. & when they found them they were just about done they had to carry MacIntosh into the hut where the two of them where laid up for 4 days so things where only fair down there then we started exploring south Victoria land where we nearly lost the ship a dozen times we were all glad to get out of that place, back towards the hut searching all the time for Prof David [Professor Tannatt William Edgeworth David] and his party [Douglas Mawson and Dr. Alistair Forbes MacKay] so we had the good luck to pick them up then.

HIS SUBSEQUENT LIFE

From Poplar, WFW made his way back to Australia where in Sydney he married Elizabeth Grace Smith in 1911. Back in Tasmania, WFW was always restless and he tried his hand at a number of jobs including policing in Hobart and Launceston, and working for the railways at Andover before going on to manage, for the Tasmanian Government, a number of guest houses catering for trout fishermen.

After a few years at Lake Leake the family moved to Interlaken, located on the shore of Lake Sorell. Here the fishing was again superb, the lakes were not overfished;



PLATE 2
The Rainbow Chalet.

indeed most of the guests arrived in horse-drawn coaches and sulkies as motor vehicles were still a rarity. When the fish weren't biting, WFW's younger son (William Reginald Williams) recalled:

Alternative methods had to be used. When one is running a resort and you cannot put trout on the menu, your credibility goes for nought, so when we could not catch them fair dinkum, after dark I would slip a sock over the rowlocks of the dinghy and move silently to a quiet corner, connect my spot light to my motor bike battery, grab my long handled gaff and in quick time have enough trout for breakfast. The guests were amazed as there was no refrigeration in those days in the Lake country. I used to tell them about the "lucky luminous" spinner I used.

Smoked eels were also a favourite and WFW and his younger son used to set a tail net in the creek that runs between Lake Crescent and Lake Sorell from where they

could always guarantee a good catch. One morning there was a bonus when they retrieved the net – a beautiful 29½ lb (13.4 kg) brown trout. But the fish, which was badly net-marked, had been caught out of season and illegally so they did the only sensible thing and ate it.

From Interlaken, WFW and his family moved on to the Great Lake where in 1929 they opened the brand new Rainbow Chalet (pl. 2). This building could accommodate 50 paying guests. Anglers from all over the world came to stay at what was considered the best trout fishing venue in Australia where rainbows averaged 3½lbs (1.5 kg) and brownies 5½ lbs (2.5 kg) (pl. 3).

Notable guests included Robert Baden Powell, founder of the Scouting Movement. He stayed for a few days in April 1932. On the last day of the season Baden Powell was out with WFW's son. It was particularly cold and bleak, and they hadn't caught a thing. Deciding to call it a day as darkness fell, Baden Powell caught an 8 lb (3.6 kg) rainbow whilst winding in his line just as the launch got back to the jetty (pl. 4).

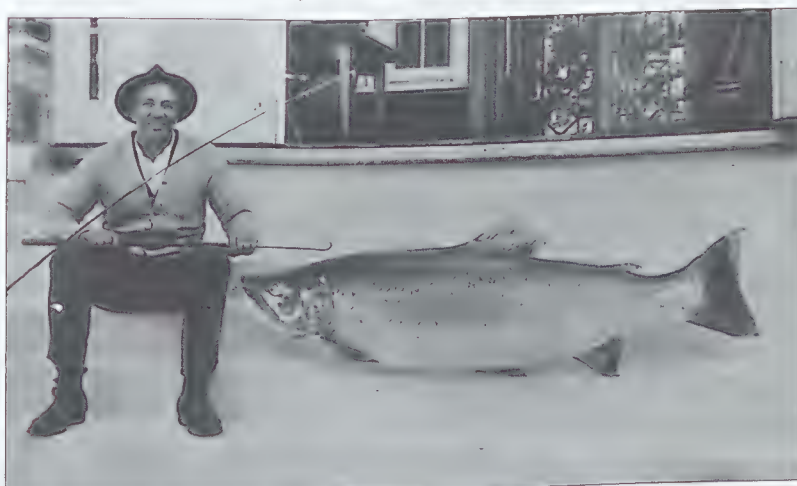


PLATE 3

WFW seated on the steps of the Rainbow Chalet with the monster trout used in advertising photographs.



PLATE 4

Robert Baden Powell with the 8-lb rainbow trout he caught on the last day of the 1932 season.

The Australian and England Test Cricket teams also visited. In the days before air travel the Australian team would tour Tasmania before going overseas. Douglas Jardine, captain of the infamous bodyline test series of 1932–33, also spent a week there. He possessed some fine trout fishing equipment, mostly from Hardy Brothers – equipment valued at £400 (\$800) at a time when the weekly tariff at the Chalet was £5.12.6d (\$12), all meals, morning and afternoon tea included.

The Williams subsequently moved to Victoria where WFW tried chicken farming in Werribee with his elder son Claude but ended up as a cobbler at Williamstown. In the late 1940s WFW retired to Eastern View, Victoria, purchasing a gracious house with outstanding views towards Lorne some 11 km away. Here he cleared the land behind the main house and built a small shack where he would live when the house was let to holiday makers. WFW was a wonderful, enthusiastic gardener, providing the local guest houses with home-grown fruit, vegetables and flowers. He was renowned for his strawberries and gladioli.

William Frederick Williams died in Elsternwick private hospital, Melbourne, on 25 July 1964, from emphysema – he had been a heavy smoker all his life. He was 77 years old.

ACKNOWLEDGEMENTS

I thank Marion Downies (WFW's granddaughter) for access to family papers and photographs including notes for an interview given by WFW's younger son for a 1980s fishing magazine (untraced).

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(accepted 3 November 2009)

AN ESTIMATE OF CHANGE IN A SUB-POPULATION OF *LOMATIA TASMANICA* (PROTEACEAE) BETWEEN 1993 AND 2008

by Jayne Balmer

(with seven text-figures and one table)

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A decline in ramet (plant stem) numbers was observed within a sub-population of *Lomatia tasmanica* W.M. Curtis between 1993 and 2008. The mortality was mainly among the small ramets. This resulted in a shift from a population dominated in density by recent suckers and young ramets to one dominated by more mature ramets. There was possibly an increased survival rate among ramets cut for genetic sampling in 1993 compared with those that were not pruned. It is suspected that a combination of reduced rainfall and declining light availability has resulted in an increased mortality among young ramets. Although this species is entirely reserved within the Tasmanian Wilderness World Heritage Area it is still vulnerable to random events and climate change and its status as critically endangered remains appropriate.

Key Words: threatened plant monitoring, pruning impact, climate change, Southwest National Park, Tasmania, *Lomatia tasmanica*.

INTRODUCTION

Lomatia tasmanica W.M. Curtis (King's Lomatia) is a member of the plant family Proteaceae Juss. and is listed as critically endangered under the Australian Government's *Environmental Protection and Biodiversity Conservation Act 1999*. The plant reproduces vegetatively by sending up new plant stems, defined here as ramets, from underground rhizomes (Brown & Gray 1985). In December 1993 surveys by J. Balmer and others mapped all ramets within one transect region (Lynch & Balmer 2004) and sampled leaves and population densities from across the known geographic range of the species to determine the genetic variability of the population and estimate the total population of the stand. The genetic study revealed that the population was composed of a single genetic clone (Lynch *et al.* 1998). Chromosome counts led to the conclusion that the species is a sterile triploid relying entirely on vegetative regeneration for its survival (Lynch *et al.* 1998, Threatened Species Section 2005). A fossil record of the species from Melaleuca (–43°25'S 146°10'E) in southwest Tasmania provides evidence that this clonal plant may have been in existence for 43 600 years (Jordan *et al.* 1991, Lynch *et al.* 1998).

Data from surveys conducted between 1993 and 1996 provided a population estimate for the plant clone of 600 ramets (stems) (Lynch & Balmer 2004). The total extent of the species is now thought to be about 1.2 km within the Southwest National Park in Tasmania (Lynch *et al.* 1998, Threatened Species Unit 2000, Lynch & Balmer 2004). The habitat for the species ranges from wet scrub to rainforest with most of its extent occurring within riparian areas of mixed forest (Brown & Gray 1985, Lynch & Balmer 2004).

The recovery plan for *L. tasmanica* recommends that population monitoring be undertaken “to find more out about this unique species” (Threatened Species Section 2006, p. 15). Monitoring of threatened species is essential to determine if populations are contracting and require management intervention in order to avert further decline and extinction. *L. tasmanica* has World Heritage significance as an example of the longest-lived plant clone known in the world and has had intense international publicity (Balmer

et al. 2004). Despite the success and advantages of asexual reproduction (Cook 1985) *L. tasmanica* is one of only a few vascular plant taxa that are known to reproduce entirely by asexual means. A few other examples also occur within the family Proteaceae including the endangered clonal shrub *Hakea pulvinifera* L.A.S. Johnson (Smith 2004). As one of just a few taxa exhibiting this trait, *L. tasmanica* provides a useful example to test the evolutionary hypothesis that following the extinction of their sexual ancestors, clones will inevitably become extinct without taxonomic descendants (Grant 1981).

This region of southwest Tasmania has experienced a substantial and linear decline in rainfall over the past decade (Bureau of Meteorology data for Maatsuyker Island, Kirkpatrick *et al.* 2002), with some areas recently receiving less than the 50 mm summer monthly rainfall considered necessary to maintain rainforest (Jackson 1968). This raises the question of how climate change might impact on plant dynamics within rainforest – especially small relict patches. This further increases the scientific and conservation management interest in monitoring *L. tasmanica*, one of the few plants to have been intensely surveyed in the region prior to the reduction in annual and summer rainfall.

Another reason for monitoring has been the concern that taking cuttings from *L. tasmanica* plants may cause shock or allow disease to invade plants, leading to the death of sampled plants in the wild. Potential threats to the species are posed by naturalists and gardeners illegally taking stem samples to propagate the species for horticulture; such visits also increase the potential to introduce disease into the population.

In response to the threatened species recovery plan recommendations and concerns about both the impact of recent rainfall declines and the taking of cuttings from the wild population the area surveyed in 1993 was resurveyed in March 2008. This paper explores the relationships observed between the 1993 and 2008 survey data and tests the following two null hypotheses: (1) the population size and demography of the *L. tasmanica* stand has not changed between 1993 and 2008; and (2) the health of *L. tasmanica* ramets from which cuttings were taken is no different from plants from which stem cuttings were not taken.

METHODS

1993 survey (unpublished DPIW data, Lynch & Balmer 2004)

A 75 m transect line was run out using a tape measure in straight line sections so that it more or less followed the creek-line. The changing direction of the transect was recorded in degrees (magnetic) using a Sunto compass and the distance in metres to each bend was noted.

All ramets of *L. tasmanica* observed within 10 m either side of the transect line (an area of ~1.5 ha) were recorded together with:

- the distance away from the creek in an approximately eastern (+ve) or western (-ve) direction
- the distance up from the beginning of the transect (~northwards)
- an estimate of height or ramet length (to the nearest 500 mm)
- the stem diameter in millimetres measured at the base using a diameter tape
- the number of upright ramets arising from a basal rhizome
- notes on the plant health
- a note recording if a cutting was taken
- a ramet identification number.

If a main stem (ramet) was obvious (even when leaning or horizontal) it was recorded and mapped at its point of origin from the ground. However, where a basal horizontal stem was present very close to the ground with more than one main leader arising from it and behaving as individual trees then each of these main leaders was treated as an individual ramet for the purposes of the census.

Flagging tape was tied to each *L. tasmanica* ramet found to make it clear that they had been recorded. All ramets from which cuttings were taken and an equivalent number of control ramets were tagged with stainless steel measuring labels loosely hung around the branch with the wire enclosed in plastic tubing to protect the plant from abrasion or damage from the tag.

2008 census

In March 2008 all ramets at the site were mapped following the method used in 1993 and an attempt made to match ramets with the original ones located in 1993. The ramets that still bore numbered metal tags or labelled flagging tape were matched precisely with the 1993 survey data. Due to the imprecision of the mapping in 1993 and time constraints for the remapping in 2008 it was not possible to precisely match all ramets between the two sampling periods. Where a plant was located within a metre of a ramet mapped in 1993 this plant was assumed to be the ramet mapped in 1993. Exceptions to this occurred if the ramet in 2008 bore no flagging and was considered too small to have been present in 1993. Three ramets were located in areas where no ramet was mapped in 1993 (including one dead ramet). However, these bore flagging tape suggesting that they had been recorded and had probably been mis-mapped. Final tallies were adjusted to take these probable data collection errors into account.

The software package, *MapInfo Professional* was used to plot the 1993 transect and 1993 and 2008 ramet distributions (figs 1, 2).

Statistical analysis

The non-parametric Mann-Whitney (Wilcoxon) W test was used to test if the median stem diameter, stem height or length and distance to the creek were significantly different between the 1993 plants that survived to 2008 compared with those that had died by 2008. The Chi-squared test was used to test whether mortality was independent of height, stem diameter and the impact of stem cutting.

All living ramets recorded in each of the two time periods within the transect area were used to analyse the significance of population structural differences between the two time periods. The significance of the difference in median values of stem diameter and height of the 2008 and 1993 population was tested using the Mann-Whitney W test. Linear regression and multi-factor analysis of variance was used to test the relative importance of each factor on the survival of plants.

The student t-test was used to compare the difference in the mean climatic data for the 14 years preceding the 1993 and 2008 monitoring visits and the long-term weather data for Maatsuyker Island (the nearest weather station). All tests were performed using the software package, *Statgraphics Plus for Windows* (Manugistics 2000).

RESULTS

The total number of living plant stems of *L. tasmanica* observed in the survey area changed from 103 in 1993 to 84 in 2008, a decline of 18%. Eight ramets observed in 2008 were small (<3 cm diameter or <600 mm high) and likely to have regenerated since 1993 (10% of the 2008 population). Fourteen unmarked ramets observed in 2008 could not be matched to the 1993 mapped ramet locations and were estimated to be larger than plants arising since 1993. These unmatched ramets were assumed to have been overlooked in 1993. A total of 41 plants of the 103 live plants recorded in 1993 were either dead or not located and were presumed to have died since 1993 (table 1). Excluding the 2008 unmatched mature plants from the population statistics the decline in plants recorded in 1993 was around 32% (table 1). If they are added to the original population numbers the decline was 28%.

The survival rate was significantly higher among plants from which cuttings were taken. Only three of the 16 plants sampled from the transect area were found dead in 2008 or not relocated. The Chi-square test with Yates correction factor was only significant at the 90% level ($p < 0.1$).

Plants that died prior to March 2008 had significantly smaller diameters and heights in 1993 than those that survived ($p < 0.01$, and $p < 0.05$, figs 3, 4). The relationship of plant survival and the parameters – stem diameter, height and cutting – was weak and the fitted linear regression models for each of these factors, while all significant ($p < 0.05$), explained only 7%, 7% and 5% respectively of plant survival. A regression analysis of height and stem diameter showed that they are significantly correlated ($p < 0.0001$) while the choice of stems cut was not correlated with either stem diameter or height ($p > 0.1$). A multi-factor analysis of variance in survival rate was used to test the relative significance of the contributions of the three factors, height, stem diameter and stems cut. Height and stem cutting each contribute significantly to the variation in survival rate (both



FIG. 1 — Map of ramets in 1993 within 10 m of the transect-line. The inset map of Tasmania shows the location of the transect (large dot) and the location of the Maatsuyker Island climate station (star).

FIG. 2 — Map of ramets in 2008 within 10 m of the transect-line.

TABLE 1
Tally of plants recorded in 1993 and 2008

Population parameters	Tally of live ramets	Tally of dead ramets
Total no. of ramets observed in 1993 [P1]	103	5
Total no. of ramets observed in 2008	84	11
Live 2008 ¹ [L] and dead 2008 [D1]	62	11
Unmatched plants regenerated since 1993 [R]	14	0
Unmatched plants (possibly overlooked in 1993)	8	0
Ramets not relocated in 2008 presumed to have died ² [D2]	—	30
Regeneration rate 1993–2008 [R/live live P1] ³	8%	—
Mortality rate 1993–2008 [D1+D2/live P1] ³	—	40%
Population change 1993–2008 [1–{(L+R–D1–D2)/live P1}] ³	—	–32%

¹ Two live and one dead ramet were marked but did not match locations of any of the plants mapped in 1993.
² The marked ramets located in areas not matching the original mapped locations were subtracted from the tally of missing plants.
³ Calculations exclude unmarked mature ramets observed in 2008 not observed in 1993.

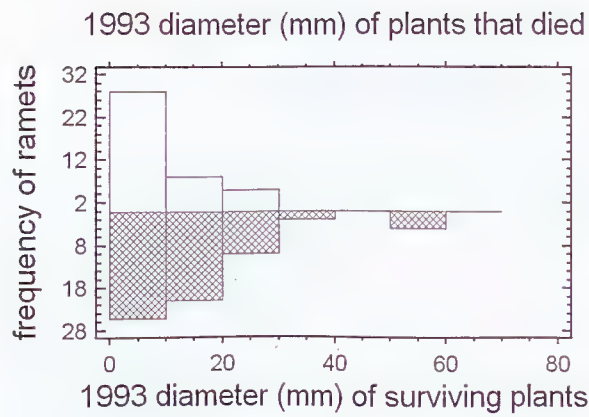


FIG. 3 — Histogram of diameters for the 1993 ramets that survived to 2008 and those that had died by 2008.

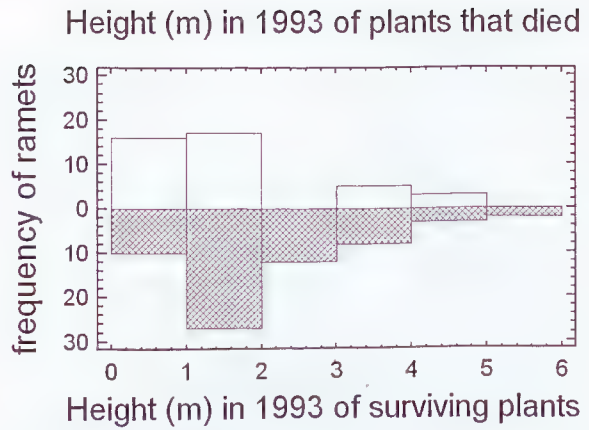


FIG. 4 — Histogram of heights for the 1993 ramets that survived to 2008 and those that had died by 2008.

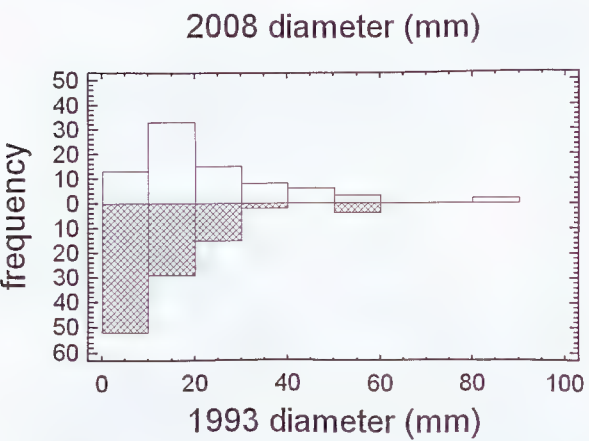


FIG. 5 — Histogram showing changes in population ramet diameters between 1993 and 2008.

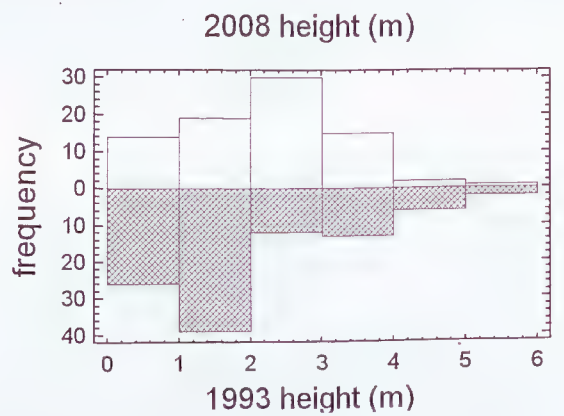


FIG. 6 — Histogram showing changes in population ramet heights between 1993 and 2008.

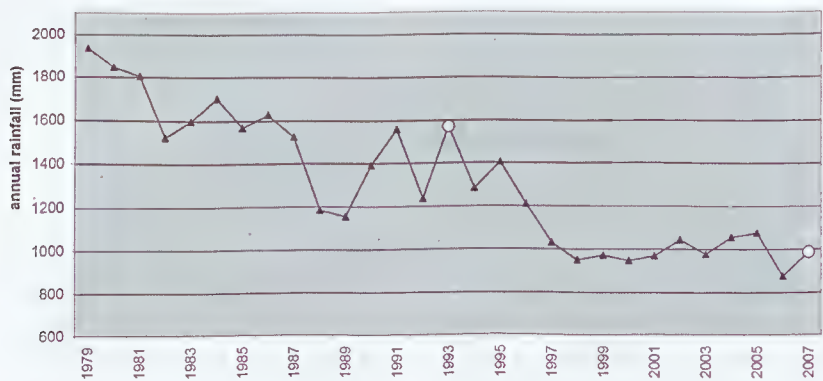


FIG. 7 — Annual rainfall at Maatsuyker Island climate station 1979 to 2007.

$p < 0.05$) but stem diameter did not provide any additional explanation of the variation ($p > 0.05$).

The median diameter and height of ramets was significantly different between the two time periods ($p < 0.01$ and $p < 0.0001$ respectively), and the population structure had also changed significantly ($p < 0.05$) between the two time periods. There were significantly fewer new suckers and young ramets than were recorded in 1993 (fig. 5). Stem diameters and height had increased since 1993 (fig. 6).

There was no statistically significant association between ramets that died and their proximity to the creek-line ($p > 0.1$).

Weather data from Maatsuyker Island (Bureau of Meteorology data) indicate that the 14 years preceding the 2008 monitoring trip had significantly less annual precipitation than the 14-year period prior to the 1993 monitoring trip ($p < 0.0001$, fig. 7) as well as being significantly drier than the long-term average ($p < 0.02$). The 14 years preceding 1993 in contrast were significantly wetter than the total 116 years of records ($p < 0.001$). Likewise, the average precipitation for all months was less between 1994 and 2008 compared to the 14-year period up to 1993. All but February and March had significantly different mean values for monthly precipitation ($p < 0.05$). Regression analysis showed there was a significant linear decline in rainfall between 1980 and 2008 ($p < 0.0001$).

With the exception of April there was no significant difference in average annual or monthly maximum or minimum temperatures for the two 14-year periods prior to monitoring ($p > 0.1$). For April the mean monthly minimum temperatures and mean monthly maximum temperatures for the period 1980 to 1993 were warmer (by less than 1°C) than both the long-term average ($p < 0.05$) and for the period 1994 to 2007 ($p < 0.05$). Temperatures for the 14-year period prior to the 2008 monitoring survey were not significantly different from the long-term average.

DISCUSSION

Several problems made the accurate mapping of the *L. tasmanica* ramets challenging. The species is cryptic in the dark rainforest understorey in which it occurs. In the wild it typically has a slender, spindly, etiolated form, with few lateral branches on which leaves are generally confined to the apex. *L. tasmanica* regenerates vegetatively by suckering from underground rhizomes and basal stems, creating confusion for the mapping of individuals. Fallen tree limbs and trees within the site surveyed were common and have resulted in the accumulation of dense litter and branch wood on top of the *L. tasmanica* plants. Due to this and the flexible habit of the species, some of the *L. tasmanica* plants have fallen over and the lateral branches have become vertical leaders creating further ambiguities for mapping.

Population stability

Despite the low precision in matching the ramets between the two time periods, it is clear from the data that there has been a real decline of between 18% and 32% in ramet numbers in this sub-population of *L. tasmanica* over 14 years (table 1). Therefore the null hypothesis that the population has remained stable between 1993 and 2008 must be rejected.

A similar decline across the range of the stand would have resulted in a drop from the estimated population of about

600 ramets to between 400 and 500 ramets. In addition an ex-situ collection of plants is maintained by the Royal Tasmanian Botanical Gardens (RTBG) with only a very few plants known to occur in private gardens elsewhere (Ken Gillanders pers. comm. 9 April 2009). The RTBG collection declined over the past 12 months because the number of plants that died exceeded the number of new plants propagated taking the total collection from 50 to 44. Another 52 cuttings are currently in propagation (Lorraine Perrins email, 12 April 2009).

Stand demography

Population data collected across the range of sites occupied by *L. tasmanica* between 1993 and 1996 showed the stand structure fitted a reverse J-curve consistent with a continuously regenerating species (Lynch & Balmer 2004) and consistent with many Tasmanian rainforest tree species (Read & Hill 1988). The stand demography has altered over the past 14 years at this transect site with the death of a higher proportion of the smaller ramets. The null hypothesis that the demography of the population has not changed between the time periods therefore must be rejected.

Longevity

The relationship between stem diameter and age has not been determined but Brown & Gray (1985) recorded 60 rings from a stem 2 cm in diameter and 240 rings from a stem 6 cm in diameter. On the basis of this limited information, Lynch & Balmer (2004) hypothesised that most ramets in the population postdated the widespread 1934 wild fire, with very few predating this. The presence of stems of around 8 cm diameter suggests the species may reach ages of 300 years.

The longevity of plants in horticulture is not known but the high mortality rate suggests that they are shorter lived than those in the wild. The oldest plants in the RTBG collection at present are 11 years old (Lorraine Perrins email, 14 April 2009). An older plant grown from cuttings taken in 1991 died in 2007 at the age of 16 years. *L. tasmanica* cuttings grafted onto *Lomatia tinctoria* (Labill.) R.Br. root stock may potentially have better survival rates with at least one plant propagated in this manner by Gillanders now being 24 years of age (Ken Gillanders pers. comm. 9 April 2009).

Response to having cuttings taken

The null hypothesis that the taking of stem cuttings does not lead to any changes in plant health compared with those plants which did not have stem cuttings taken requires further review, as the data showed a weakly significant association between the taking of cuttings and increased plant survival. It is possible this result may be due to a bias in the sampling towards healthier mature stems over smaller suppressed ramets. However, the lack of correlation between the taking of stem cuttings and ramet size does not support this hypothesis and the possibility that tip pruning enhanced plant vigour cannot be ruled out. Stem cuttings taken from nursery-grown plants rarely results in plant death but neither have they been observed to noticeably improve vigour or lateral branching (Mark Fountain and Natalie Tapson pers. comm. July 2008). The results indicate there is no need to restrict the taking of cuttings providing hygiene and other standard conservation measures to mitigate impacts on plant health are observed.

Possible explanations for population decline

Given that the taking of stem cuttings appears unrelated to the observed pattern of mortality, other explanations are required for the population decline observed within the transect area. The following hypotheses are explored here:

- introduction of a plant pathogen such as *Phytophthora cinnamomi*
- competition for light
- moisture stress
- disturbance from trampling during the 1993 survey.

Pathogen

Pathogenicity tests have shown that *L. tasmanica* is susceptible to *P. cinnamomi* (Rudman 2000). This plant pathogen is known to occur within the buttongrass moorland vegetation adjoining the forests in which *L. tasmanica* occurs but no tests of the soil within the stand or the creek water within the stand have been undertaken to determine if the pathogen has invaded the stand itself (Tim Rudman, Department of Primary Industries, Parks, Water and Environment Files, 8 March 2001).

It is unlikely that the recent decline in ramets could be attributable to this pathogen since studies of the summer soil temperatures in closed forest habitat similar to that along the transect have shown that these soils are too cool to support the growth and reproduction of *P. cinnamomi* (Podger & Brown 1989, Rudman 2000). Analysis of recent average monthly maximum temperature data for the region showed no significant changes in air temperatures, which is an indication that summer soil temperatures have not increased substantially in recent times although the analysis of averaged monthly data may conceal more subtle changes in climate. Nevertheless, no evidence for *P. cinnamomi*, such as ill health or death of other susceptible species, was observed within the rainforest during the various surveys and visits to the stand.

All visitors to the stand have been asked to follow strict hygiene procedures before entering the forest and visitation is discouraged. This protocol is applied widely in conservation reserves where values are at risk from the spread of this pathogen (Cahill *et al.* 2008). Here it aims to reduce the chance of introducing long-lived *P. cinnamomi* spores into habitat occupied by *L. tasmanica*. A disturbance that opens the canopy, such as fire, could enable soil temperatures to increase sufficiently for *P. cinnamomi* to become active leading to the death of susceptible species such as *L. tasmanica* as they regenerate after the fire (Podger & Brown 1989, Rudman 2000).

Light availability

Since the last fire at the site in 1934, the rainforest plants have become increasingly dominant in the understorey and it is likely that this has reduced light penetration to the ground layer. Accumulating litter and branch wood, as well as competition from other ground layer species, may be factors contributing to the higher mortality of small ramets and the reduction in the establishment of new suckers. Data were not collected on relative light availability, plant competition or understorey litter, branch wood or tree falls so that this hypothesis was unable to be tested. Nevertheless, the greater importance of height for survival and the relative lack of importance of stem diameter in the multi-factor analysis

of variance suggests that it was the plants with the greatest leaf area or leaves higher above the ground that were more likely to survive. These plants are likely to intercept a greater amount of light.

The vigour of plants in the wild is poor compared to plants grown in gardens and nurseries where light is more freely available and competition is reduced suggesting that light may be a limiting factor in the wild. Nevertheless the species is very sun-sensitive and requires shade (Mark Fountain and Natalie Tapson pers. comm. July 2008). A study of ramet response to light variation in a species of bamboo showed that low light conditions inhibited the production of ramets, and resulted in ramets with longer internode lengths but no mortality was recorded (Yue *et al.* 2004).

Moisture stress

The average rainfall for the region in the 14-year period up to 2008 was c.1000 mm per year, much lower than the preceding 14-year period when it fluctuated between 1200 and 1800 mm (fig. 7). This has shifted the rainfall closer to the lower limit for the maintenance of rainforest vegetation of about 1000 mm average annual per year and 50 mm average summer monthly rainfall (Jackson 1968). The higher than average rainfall experienced in the years leading up to 1993 may have given rise to an increased production of ramets that have subsequently died. Kirkpatrick *et al.* (2002) suggested that a decline in graminoid and herb cover in the alpine vegetation on the Southern Ranges between 1990 and 2000 may have been related to the significant linear decline in rainfall between 1980 and 2000. No other study in southwest Tasmania has looked at vegetation responses to recent climatic changes.

Reduced moisture availability is known to reduce the production of proteoid roots in some members of the Proteaceae (Lamont 1986). In general, plants with proteoid roots are able to extract phosphorous from nutrient-deficient soils more effectively than other plants, even those with mycorrhizal associations (Pearson & Rengel 1997). If *L. tasmanica* has such roots it is possible that if moisture levels are reduced then the plant's ability to absorb phosphorous will decline, reducing its competitive ability in this low-nutrient environment.

Spatial distribution of plant death

The spatial pattern of the dead plants relative to the living population was not statistically tested for its deviation from random. The disturbance from survey work is likely to have been relatively evenly distributed across the population or concentrated in the region of the creek-line where the transect-line was located. However, the deaths appear to be loosely clustered in patches rather than being evenly dispersed or concentrated along the creek-line, so there is no apparent relationship between the site survey conducted in 1993 and the pattern of deaths observed.

Plants with proteoid roots, such as those in the genus *Lomatia* and many other members of the Proteaceae (Purnell 1960), may be particularly sensitive to root disturbance (Lamont 1986). Certainly the disturbance of potting up plants and moving them is strongly associated with an increased mortality (Lorraine Perrins pers. comm. July 2008 and April 2009). A recent death of the most mature pot plant in the RTBG collection followed the removal of liverworts from the soil surface. Tests did not reveal the cause

of the death but the symptoms of sudden blackening of all the leaves suggested that the plant may have been shocked by the light root disturbance causing the release of toxic phenolic compounds which led to its death.

Given the apparent sensitivity of this species to root disturbance some impact from trampling during the survey of 1993 cannot be dismissed.

Clonal plant responses to resource limitations

Each ramet of *L. tasmanica* is part of a larger colonial plant. The duration of the connections between *L. tasmanica* ramets is not known but studies of *Populus* showed that root connections between clonal trees may persist for up to 50 years while others decay quickly (Pitelka & Ashmun 1985). Clonal plants can, and regularly do, share resources (Cook 1985, Pitelka & Ashmun 1985). They are also able to "forage" by altering their growth in response to resource availability, but despite this their success may be dependent on the spatial arrangement of suitable habitat (Cain *et al.* 1996). Observations and ecological theory about dynamics of clonal populations suggest that the parent plants typically expend energy to support their daughters and that this leads to a higher rate of establishment by clones compared with seedlings (Thomas & Dale 1975, Cook 1985). Populations are fairly stable over long periods of time with increases in appearance of new plants tending to be associated with increased rates of mortality which are typically seasonal (Noble *et al.* 1979, Fletcher & Shaver 1983, Cook 1985). More recent theoretical models suggest that habitat patchiness and variability is likely to determine whether the strategy of maintaining integration between clonal plants is more advantageous to the genet than the strategy of splitting clonal progeny from parent plants (Kun & Oborny 2003, Mágori *et al.* 2003). Since the degree to which *L. tasmanica* splits or remains integrated is unknown, the implications of this on its capacity to respond successfully to changes in habitat remain unclear.

CONCLUSIONS

The results of this study show the importance to conservation management of longitudinal studies to monitor changes in the population of threatened species and the risks of placing too much reliance on the results of single surveys. They also highlight that threatened species are vulnerable both within and outside the reserve system. Species restricted to the reserve system may be vulnerable to benign neglect by land managers struggling to find sufficient funds to manage the growing reserve system.

It is probable that the decline in numbers of ramets observed in the transect area is part of a natural response to climatic variation and/or light availability. A study of the size class structure of *L. tasmanica* across its range is needed to determine if the decline observed in this sub-population is part of a more widespread trend.

While there has been a decline in younger plants, the survival of the mature plants suggests that the sub-population is not under immediate risk of local extinction. Regeneration is still occurring albeit at a lower rate than previous observations suggested. If declining rainfall is responsible for the population change then further drying may well have serious implications for the regeneration dynamics and survival of *L. tasmanica* in the region. Its presence within a

national park in the Tasmanian Wilderness World Heritage Area does not offer any protection against this threat. Other species with limited dispersal capacity and sensitivity to drought are also likely to be at risk from declines in local regional rainfall. While climate modelling for the Tasmanian and Australian region has not yet predicted any significant changes in the climate of southwest Tasmania it is based on very limited data and hence has a low reliability for this region (McIntosh *et al.* 2005, CSIRO & the Australian Bureau of Meteorology 2007).

Given the threats to the wild population of *L. tasmanica*, the maintenance of an ex-situ population of the species is important (Threatened Species Section 2006). Although a clone, the low rate of survival of plants in horticulture suggests that the ex-situ collection should be no less than 50 plants. The establishment of longer lived material by grafting onto hardy root stock would also be a sensible precaution. The development of a cheap, mass propagation technique for the species would enhance the long-term survival chances of the species by:

- increasing the total number of extant plants in horticulture
- reducing the need to visit the wild population in order to see the species
- reducing the illegal taking of cuttings from the wild
- enabling the efficient propagation of the species for replanting in the event of a wildfire or any other catastrophic event destroying the wild population.

A first attempt to develop a tissue culturing technique for the species was begun at the University of Tasmania in 1994 (Cambecèdes 1995). This research is continuing as a collaborative project between the University of Tasmania and the RTBG (Anthony Katoulis and Lorraine Perrins pers. comm. April 2009) and the project's continuation is recommended.

Further ecological studies of *L. tasmanica* are also desirable if there is to be any chance of understanding and conserving this unique species in the wild. Priority research questions include:

- Does *L. tasmanica* have proteoid roots and what ramifications does this have for horticulture?
- How sensitive to trampling impacts is the plant and what measures can be taken to minimise impacts of visitation to the wild population?
- How long do ramets maintain connections with each other? This has ramifications on stand maintenance through resource sharing and partitioning.
- Is light or other competition a limiting factor for regeneration of the species in the wild and if so could it be alleviated by active canopy thinning or removing of competing species, dead branchwood and other litter?
- What prompts the formation of new ramets, and what is their growth rate?
- Are current summer soil temperatures sufficiently low to protect the species from being impacted by *Phytophthora cinnamomi* should it invade?
- Are spores of *P. cinnamomi* already in the soil within the *L. tasmanica* stand?

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FORAMINIFERA AND PALAEOENVIRONMENT OF ELEVATED LATE PLEISTOCENE SANDS, WHITE ROCK POINT, SOUTHEASTERN TASMANIA

by Dale Lewis and Patrick G. Quilty

(with three text-figures, one plate, one table and one appendix)

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A well-preserved foraminiferal fauna similar to that living in nearby Ralphs Bay in southeastern Tasmania is documented from raised shallow-water sediment of 130–119 Ka age (Late Pleistocene; Marine Isotope Stage 5e) at about 24 m above modern sea level on White Rock Point. Foraminifera and sediment characteristics indicate that deposition occurred in very shallow, highly oxygenated, high-energy marine conditions in an area of open circulation. There is very little infauna. The locality is the only known site for such a fauna from before human habitation of the Derwent Estuary region, and allows comparison with modern faunas.

Key Words: Pleistocene, Foraminifera, palaeoenvironment, Tasmania.

INTRODUCTION

Much has been written since the visit of Charles Darwin to Hobart in 1836 (Darwin 1891, Sutherland 1971, Banks 1971, Bowden & Colhoun 1984, Banks & Leaman 1999, M. Davies 2009) concerning possible “young” uplift or neotectonic activity of Tasmania. Darwin (1891) discussed briefly evidence in the form of raised shell beds in the vicinity of Hobart, and Banks (1971) and Banks & Leaman (1999) expanded on that comment, using Darwin’s own diaries. Unfortunately, many of the localities Darwin visited are now altered or inaccessible because of development. Darwin referred to the then current belief by the “colonists” that most shell beds were the result of transport by Aborigines but his view was that “... the greater number [is due] to a small elevation of the land” (Darwin 1891 p. 158).

The question of rejuvenation of tectonically-controlled land level and its causes has become of recent interest with the need to differentiate evidence of land elevation change versus sea level change (Dickinson *et al.* 2002, Sandiford 2003, 2007, Sandiford *et al.* 2004). Tasmania has several recognised surfaces such as the Milford (c. 1 m above modern sea level) and Llanherne (4 m) surfaces of J.L. Davies (1951, 1961) who ascribed changes in level to variation in sea level. The Milford level was associated with a sea level highstand at 6–Ka. His papers did not refer to the higher level sediment studied here.

Unconsolidated sediment to 24 m above sea level (m.a.s.l.) occurs on White Rock Point (42°58'S, 147°24.3'E), on the peninsula immediately north of Opossum Bay, southeastern Tasmania (figs 1, 2). This is recorded as Mary Ann Bay sandstone on Leaman (1972). The sediment is not of middens, which do occur nearby, but undisturbed natural sediments, lying where deposited. This site, commonly referred to as Mary Ann Bay, is critical in the discussion of uplift because it appears to be the sole locality in the Tasmanian region which has yielded fossil-based information on elevation and age, thus allowing an estimate of rates of change of uplift. The sediments contain the only known “young” fauna from pre-human activity in the region.

The sediment has been dated by Murray-Wallace *et al.* (1990) and Murray-Wallace & Goede (1991, 1995) to the Last Interglacial Maximum, Marine Isotope Stage (MIS) 5e or 130–119 000 years, using amino acid racemisation and electron spin resonance techniques. These ages suggest deposition when sea level may have been a few metres above current (Hearty *et al.* 2007) but the true sea level difference depends on where, in the interval 130–119 Ka, the age of the sediment falls. This is unclear as yet. The subject of precise dating of, and sea level variation during, the Last Interglacial interval is contentious at present (Edwards *et al.* 1987, Szabo *et al.* 1994, Slowey *et al.* 1996, Muhs *et al.* 2002) and other dating techniques such as U/Th may be useful in placing this material in the context of climate change controlled by orbital forcing (the Milankovitch hypothesis).

The sediment is described in detail by Murray-Wallace *et al.* (1990). It consists of well-sorted quartz sand from more than one immediate source and contains grains, dominantly medium sand fraction, that vary from very well rounded to fresh, angular, commonly with some crystal faces indicating recent release from local high porosity Triassic sandstone. The sediment is cross-bedded and most molluscs are highly fragmented, suggesting deposition in shallow marine, high-energy conditions typical of small bays currently found around the peninsulas of South Arm and Tasman Peninsula (fig. 1). The sediments contain a diverse fauna of extant molluscs (Colhoun *et al.* 1982).

In addition to the molluscs, the sediments contain a significant foraminiferal fauna of species that are well-known in the vicinity (Harris 1969, Lewis 2006). They are well-preserved and thus allow comparison of conditions between pre- and post-human, occupation of the region, including geochemical signals in the calcium carbonate skeletons.

This paper documents the foraminiferal fauna, uses it to place limits on the palaeoenvironment at 130–119 Ka and establishes a foraminiferal baseline for southeastern Tasmanian Foraminifera from an environment that existed prior to disturbance by human activities.

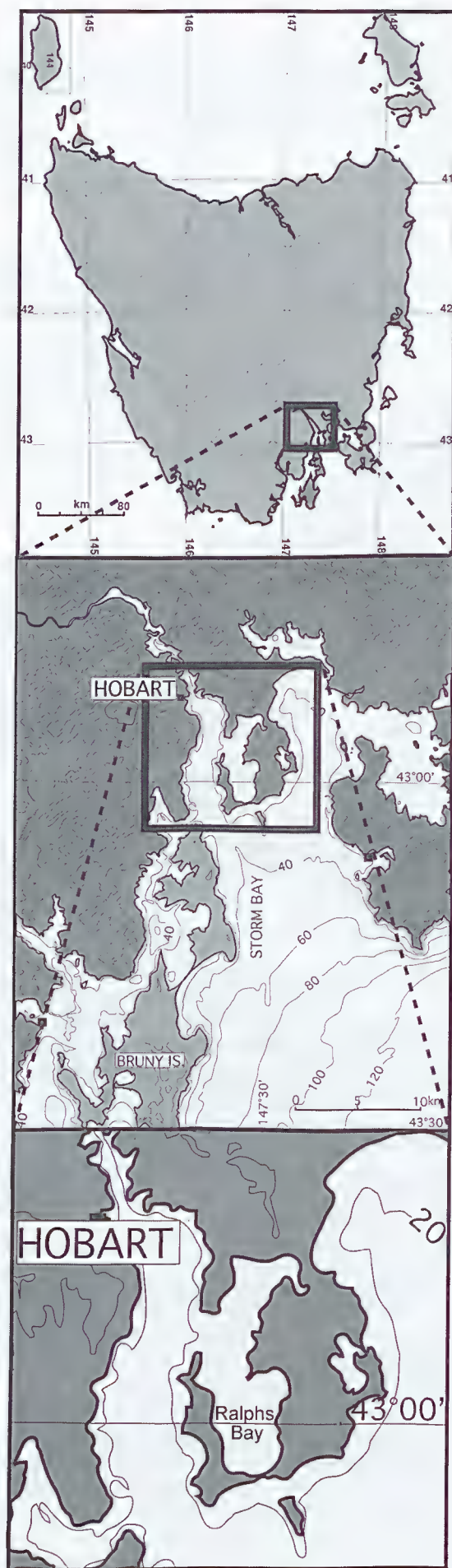


FIG. 2 — Detail of location of three specimens studied.

MATERIAL AND METHODS

Three samples (A, B and C) were collected from steep faces on the western side of the outcrop. As the sand is unconsolidated, processing consisted of simple washing of 3 x 20 g samples over nested sieves at 63, 125, 250 and 500 μ m but only those resting on sieves coarser than 125 μ m were examined. Washed residues were reduced in size by a sample splitter to yield statistically sound foraminiferal faunas; thus only 25% or 12.5% of the sample was picked to give the specimen count shown in table 1. Foraminifera were separated by standard methods, placed in cardboard slides and identified. The distribution of the Foraminifera is shown in table 1 and nomenclature followed is provided in appendix 1.

The material is well-preserved and there is no indication in the Foraminifera of damage through diagenesis although many specimens have minor abrasion or breakages consistent with a high-energy environment; thus the final chamber wall of *Ammonia aoteana* (Finlay, 1940) commonly is broken but the rest of the test is well-preserved. While the robust environment is a likely cause, the broken final chamber could also be an artefact of reproduction. There may also have been minor dissolution of test surfaces due to percolating meteoric waters but there is no evidence for significant dissolution in either molluscs or foraminiferal populations.

Species were identified using the studies by Yassini & Jones (1995), Hayward *et al.* (1999) and Lewis (2006). Once identified, a variety of standard techniques was used to categorise the fauna and to interpret the palaeoenvironment.

Samples studied and fossils illustrated are catalogued in the collection of the School of Earth Sciences, University of Tasmania, and the number following the initials UTGD is the accession number in that collection. Illustrated specimens (pl. 1) are in the range 128811–128822 and the hand specimens, washed residues and assemblage slides in 160918.

FIG. 1 — Locality map.

TABLE 1
Species recorded in subsets of three samples
from the western side of the Mary Ann Bay
outcrop

Species	Sample A	Sample B	Sample C
Benthic species			
<i>Ammonia aoteana</i>	87	76	37
<i>Bulimina gibba</i>	2		
<i>Cibicides refulgens</i>	16	8	1
<i>Elphidium advenum advenum</i>	6	8	5
<i>E. advenum maorium</i>		1	
<i>E. crispum crispum</i>	3		3
<i>E. excavatum clavatum</i>	5	2	
<i>E. hawkesburiense</i>	27	33	10
<i>Notorotalia clathrata</i>	10	2	4
<i>Parrillina verriculata</i>		1	
<i>Trifarina pacifica</i>	1	1	
<i>Uvigerina bassensis</i>	1		
Planktonic species			
<i>Globigerina bulloides</i>			1
Total	157	132	61
Specimen count/20 gm	628	1056	488
Diversity	6	4	4
Dominance	55	58	61
Fisher a Index	3	3	2

FORAMINIFERAL FAUNA

The fauna is remarkably similar between samples. Diversity is low as expected in the palaeoenvironment envisaged. *Ammonia aoteana* is dominant (55–61%). The next most abundant species is *Elphidium hawkesburiense* (Albani, 1974) (16–25%). Other species make up lesser proportions of the samples. Sample A contains 2% infaunal species (*Uvigerina bassensis* Parr, 1950 and *Bulimina gibba* Fornasini, 1902), and samples A and B yielded a few infaunal *Trifarina pacifica* (Albani, 1974).

Miliolids and cassidulinid species are absent as are agglutinated forms showing that there is no evidence of reduced salinity or limited circulation.

Hayward *et al.* (1999) regarded *A. aoteana* as a subspecies of *A. parkinsoniana* (d'Orbigny, 1839) but we take it to be a valid species in its own right.

Dominance/diversity

Walton (1964) studied the distribution of several hundred samples from the Gulf of Mexico and plotted diversity and dominance. Dominance (the percentage of the fauna made up of the dominant species) for White Rock Point ranges from 55 to 60, and diversity (the number of species making up 95% of the fauna) is 4–6. The corresponding Fisher a Index (Fisher *et al.* 1943, Williams 1964, Quilty & Hosie 2006) is 2 to 3. Figure 3 shows the White Rock Point samples plotted on Walton's 0–10 fathom field, suggesting that species in the samples bear the same relationship to each other in the samples as they did in life. Therefore, the faunas are neither mixed with those from any other source, and not have any species have removed from the parent sediment.

Faunal assemblage structure

There is a single occurrence of a planktonic foraminifer (*Globigerina bulloides* d'Orbigny, 1826). This is normal for sediments deposited close to a sandy beach in a shallow bay with open circulation. The ratio of infaunal/epifaunal species commonly is used as an index of nutrient supply (Corliss & Chen 1988, Murray 1991). In this case, there are very few infaunal species consistent with other evidence for a shallow-water, high-energy, highly oxygenated environment.

Comparison with nearby modern faunas

All species recovered are known locally and all are extant. Lewis (2006) has studied these species from the Pitt Water/Frederick Henry Bay area and has documented the environmental preferences of the species identified.

Deposition occurred in very shallow, high-energy, fully marine waters consistent with the evidence from the mollusc fauna discussed by Colhoun *et al.* (1982).

CONCLUSIONS

Marine sediments from about 24 m.a.s.l. at White Rock Point, southeastern Tasmania, have yielded a low diversity foraminiferal fauna typical of those to be found in the region today in shallow water, high-energy environments only a few metres deep. There is no evidence of recycling and the fauna is *in situ* and suffering only minor abrasion as expected in that environment.

Age determination by amino-acid stratigraphy and electron spin resonance has provided control to show the sediments were deposited during MIS 5e (130–119 Ka). Sea level at the time was above modern but estimates of the amount vary (2–4 m) and also depend on where in the interval the age lies. It would be worthwhile trying to limit the dates

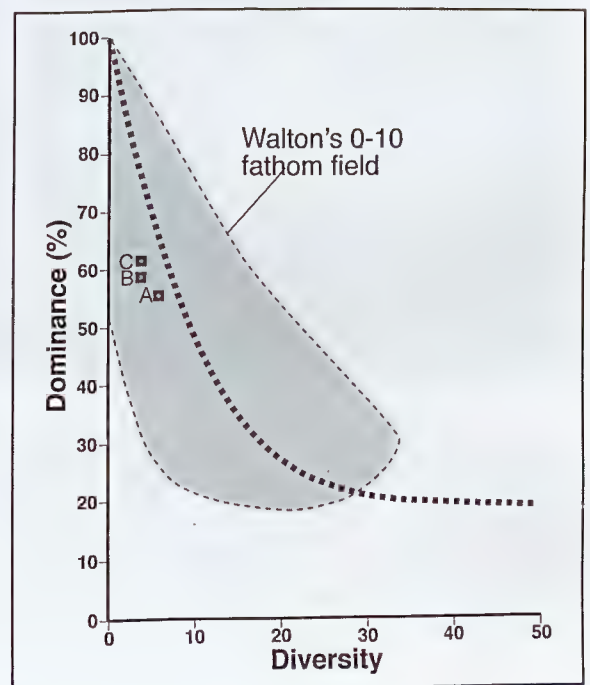


FIG. 3 — Dominance vs diversity and comparison with Walton's (1964) 0–10 fathom field for the Gulf of Mexico.

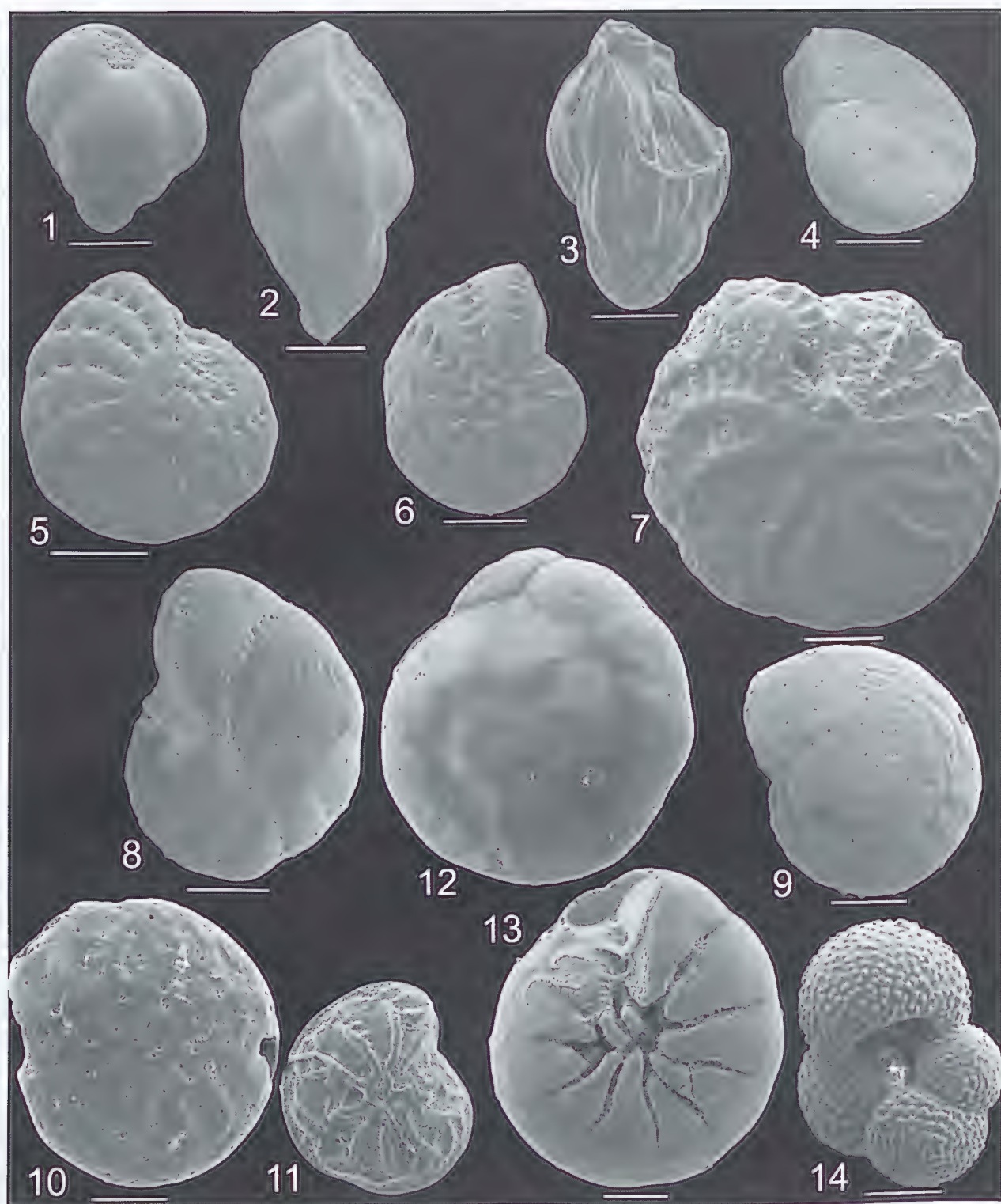


PLATE 1

Species identified from White Rock Point samples. Scale: 100 microns.

1. *Bulimina gibba*, profile view, UTGD128811; 2. *Trifarina pacifica*, longitudinal profile, UTGD128812; 3. *Uvigerina bassensis*, longitudinal profile, UTGD128813; 4. *Cibicides refulgens* de Montfort, 1808, oblique ventral surface, UTGD128814; 5. *Elphidium advenum advenum*, lateral view, UTGD128815; 6. *Elphidium excavatum clavatum*, lateral view, UTGD128816; 7. *Elphidium crispum crispum* lateral view, UTGD128817; 8. *Elphidium advenum maorium*, lateral view, UTGD128818; 9. *Elphidium hawkesburiense*, lateral view, UTGD128819; 10, 11. *Notorotalia clathrata* dorsal and ventral views UTGD128820; 12, 13. *Ammonia aoteana* dorsal and ventral views, UTGD128821; 14. *Globigerina bulloides*, apertural view, UTGD128822.

further using other techniques such as the U/Th method to allow more refined placement in the context of orbitally controlled climate change models.

The locality has been uplifted since deposition but estimates of the amount and rate of uplift rate depend on more refined age determination and of sea level at the time. The locality is the only site in Tasmania to provide information on faunas from before human habitation of the region. It would be very valuable if more such localities could be identified to further calibrate the uplift history.

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APPENDIX 1

Nomenclature followed in specific identifications

The following is not a comprehensive synonymy but provides a reference to a more comprehensive discussion of species.

- Ammonia aoteana* (Finlay, 1940)
Streblus aoteana Finlay, 1940, p. 461.
Ammonia parkinsoniana f. *aoteana*: Hayward *et al.* 2004, p. 162, pl. 16, figs 709.
- Bulimina gibba* Fornasini, 1902, p. 378, figs 32, 34.
- Cibicides refulgens* de Montfort, 1808, p. 123, p. 122, text-fig. 123.
- Elphidium advenum advenum* (Cushman, 1922)
Polystomella advena Cushman, 1922, p. 56, pl. 9, figs 11, 12.
Elphidium advenum advenum: Hayward *et al.* 1997, p. 65, pl. 2, figs 9–18.
- Elphidium advenum maorium* Hayward *et al.*, 1997, p. 69, pl. 1, fig. 7; pl. 4, figs 11–16; pl. 5, figs 1–5.
- Elphidium crispum crispum* (Linné, 1758)
Nautilus crispus Linné 1758, p. 709
Elphidium crispum crispum: Hayward *et al.* 1997, p. 74, pl. 7, figs 13–16; pl. 8, figs 1–9.
- Elphidium excavatum clavatum* Cushman, 1930
Elphidium incertum (Williamson) var. *clavatum* Cushman, 1930, p. 20, pl. 7, figs 10a, b.
Elphidium excavatum clavatum Cushman, 1930: Hayward *et al.* 1997, p. 76, pl. 8, figs 141–7; pl. 9, figs 1–8.
- Elphidium hawkesburiense* (Albani, 1974)
Cribronion hawkesburiense Albani, 1974, p. 38, pl. 1, figs 12–14.
Elphidium hawkesburiense: Hayward *et al.* 1997, p. 82, pl. 12, figs 1–4.
- Notorotalia clathrata* (Brady, 1881)
Rotalia clathrata Brady 1884, p. 709, pl. 107, figs 8, 9.
Notorotalia clathrata: Yassini & Jones 1995, p. 180, figs 159–161.
- Parrellina verriculata* (Brady, 1881)
Polystomella verriculata Brady, 1881, p. 66.
Polystomella verriculata: Brady 1884, p. 738, pl. 110, fig. 12.
Parrellina verriculata: Hayward *et al.* 1997, p. 97, pl. 19, figs 1–3.
- Trifarina pacifica* (Albani, 1974)
Trimosina pacifica Albani, 1974, p. 38, pl. 1, figs. 8, 9.
Trimosina pacifica: Yassini & Jones, 1995, p. 154, fig. 62.
Trifarina pacific: Hayward *et al.* 1999, p. 134, pl. 9, figs. 25, 26.
- Uvigerina bassensis* Parr, 1950, p. 340, pl. 12, figs 19, 20.
- Globigerina bulloides* d'Orbigny, 1826 p. 277, list no. 1.
Globigerina bulloides d'Orbigny 1826: Banner & Blow, 1960, p. 3, pl. 1, figs. 1, 4.

GENETIC DIVERGENCE IN THE ASCIDIAN *PYURA PRAEPUTIALIS* (= *PYURA STOLONIFERA*) (HELLER, 1878) FROM MAINLAND AUSTRALIA AND TASMANIA

by Marcela P. Astorga, R. Guíñez and Juan C. Castilla

(with one text-figure and one table)

Astorga, M. P., Guíñez, R. & Castilla, J. C. 2009 (11:xii): Genetic divergence in the ascidian *Pyura praeputialis* (= *Pyura stolonifera*) (Heller, 1878) from mainland Australia and Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 143(2): 101–104. ISSN 0080-4703. Instituto de Acuicultura & CIEN Austral, Universidad Austral de Chile, Sede Puerto Montt, Casilla 1327, Puerto Montt, Chile (MPA*); Instituto de Investigaciones Oceanológicas, Facultad de Recursos del Mar, Universidad de Antofagasta, Antofagasta, Chile (RG); Departamento de Ecología, Facultad de Ciencias Biológicas, P. Universidad Católica de Chile, Center for Advanced Studies in Ecology and Biodiversity (CASEB), Chile (JCC). * Author for correspondence. Email: marcelaastorga@spm.uach.cl

In Australia, the sea squirt *Pyura praeputialis* is found off the mainland and off the island of Tasmania. The extent of genetic divergence between insular and mainland continental samples was determined by performing a DNA analysis using PCR–RFLP on the internal transcribed spacer region of ribosomal DNA. The two mainland populations were polymorphic and showed similar type frequencies, but both were significantly different from the Tasmanian population. This was also monomorphic, showing a unique type, absent from the two continental populations. The genetic differentiation could be explained by the lack of genetic flow observed between mainland and Tasmanian populations.

Key Words: sea squirt, genetic divergence, PCR–RFLP, ITS, Australia, Tasmania, *Pyura praeputialis*.

INTRODUCTION

The sea squirt *Pyura praeputialis* (= *Pyura stolonifera*) (Heller, 1878) is a large solitary ascidian species that occurs in dense beds on rocky intertidal reefs, from low intertidal habitats to a depth of 10–12 m along Australia's mainland and insular coasts (Edgar 1997). The species has an aggregated distribution along the rocky intertidal region (Dalby 1995) from Western Australia to Queensland and also in Tasmania (Kott 1985, Edgar 1997). These sea squirts have also been detected off the Chilean coast of South America (Castilla & Guíñez 2000, Castilla *et al.* 2002), most likely introduced there anthropogenically (Castilla *et al.* 2004).

Our study focuses on the disjunct distribution of the sea squirts *P. praeputialis* from the mainland Australian continent and Tasmania. All populations are believed to be conspecific. It is assumed that larval drift is sufficient to maintain continuous gene flow between the mainland and the island and, therefore, that Bass Strait is not a barrier for sea squirt dispersal; although some morphological differences have been reported between insular and continental specimens (Kott 1985).

Tasmania is separated from mainland Australia by the Bass Strait which is over 200 km wide. However, in the late Pliocene and Pleistocene (glacial maxima) the Bass Strait region was a dry land bridge (Knox 1980) that presumably blocked gene flow between eastern and western marine populations, also creating continuous habitats for sessile intertidal organisms currently occurring on mainland Australia and Tasmania. These geological events largely have determined the present composition of the terrestrial and marine flora and fauna, through vicariant events or dispersal driven by ocean currents (some examples are in Waters & Roy 2003, Waters *et al.* 2004, Waters 2008, York *et al.* 2008).

Any barrier, either oceanographic or habitat discontinuity, that interrupts gene flow is expected to result in increased genetic differentiation (Hedgecock 1986), and when sufficiently persistent, this can generate marine speciation

processes (Barber *et al.* 2000). Therefore, the degree of population genetic differentiation within a species can be used to determine its level of gene flow and also could permit an estimate of the isolation time, once gene flow connectivity was interrupted, thereby, allowing a reconstruction of the biogeography of the species (Wong *et al.* 2004, Waples & Caggiotti 2006, Waters *et al.* 2007).

This paper reports the first results of work in progress on the degree of genetic differentiation in marine organisms found in Tasmanian and mainland Australian localities using PCR–RFLP analysis of the internal transcribed spacer (ITS) fragments of ribosomal DNA.

METHODS

Individuals were obtained at two sites off the Australian continent (Brisbane: 27°30"S; 153°01"E, and Barwon Heads: 38°35"S; 144°30"E) and from one site off Tasmania (Kingston: 42°58"S; 147°19"E) (fig. 1).

DNA was extracted from the siphon tissue of each individual using standard phenol/chloroform/isoamyl alcohol, and ethanol precipitation extraction methods (Doyle & Doyle 1987). A PCR–RFLP was carried out on the ribosomal DNA ITS fragment, which covered the ITS-1, 5.8S, and ITS-2 fragments. The ITS primers were designed based on the conserved regions of sequences extracted from GenBank of nine different tunicate species. The design of the forward primer used sequences of the 26S gene from the following species: *Herdmania momus* (Savigny, 1816) and *Styela plicata* Herdman, 1882 (Asciacea), and *Oikopleura* sp. and *Thalia democratica* (Forsk., 1775) (Thaliacea). The reverse primer was designed using sequences of the 18S gene from the following species belonging to the family Pyuridae (Asciacea): *Pyura vitatta* (Stimpson, 1852), *P. mirabilis* (Drasche, 1884), *Halocynthia roretzi* (Drasche, 1884), *Herdmania momus*, *H. curvata* Kott, 1952, and *H. mirabilis* (Drasche, 1884). The program Webprimer (

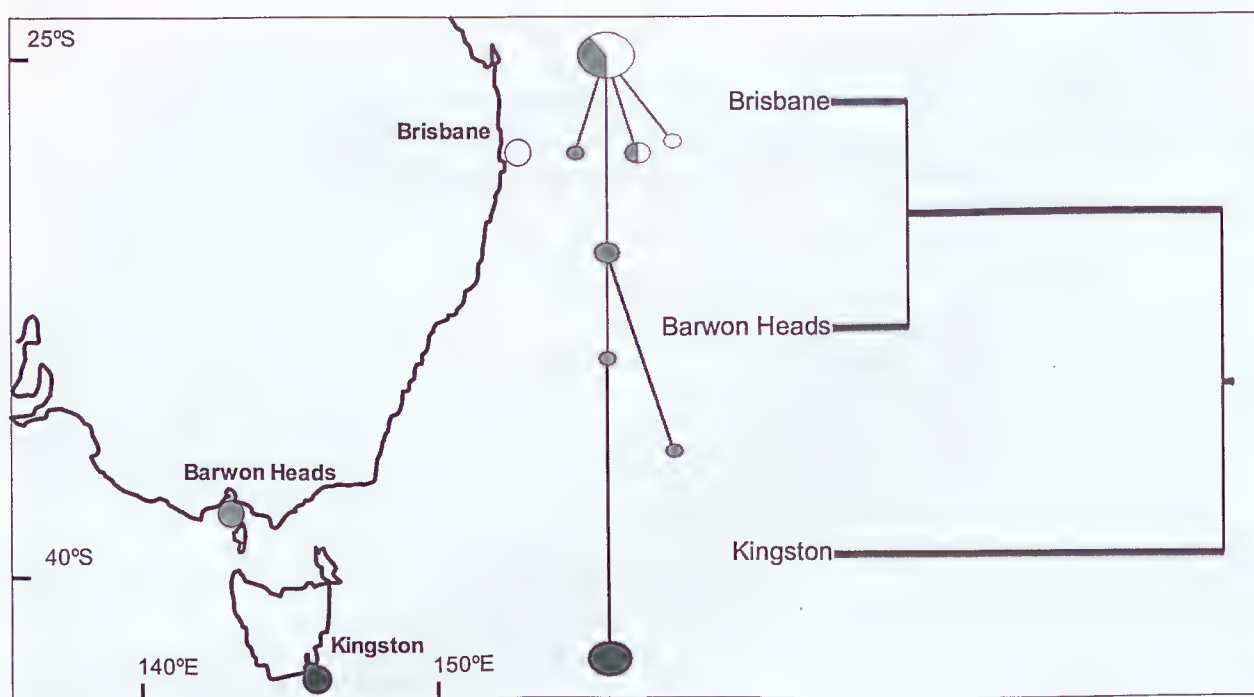


FIG. 1 — Map of the southern coast of Australia showing the analysed populations, in relation with the network analysis that groups the compound types based on their frequencies. Hierarchical clustering analysis (UPGMA) shows the relationships between the analysed populations based in Nei's genetic distance.

genome-www2.stanford.edu/cgi-bin/SGD/web-primer) was used to design both primers. The evaluation of each designed oligonucleotide was carried out using the program Net Primer software (<http://www.premierbiosoft.com/netprimer/netprlaunch/netprlaunch.html>).

PCR amplification

The ITS region was amplified by PCR using the designed primers in a mix made up of 5 μ L 10X buffer PCR (Perkin-Elmer), dNTPs 10 mM, and 4 μ L (10 μ M) of each primer, $MgCl_2$ 50 mM, purified BSA, 5 Units/mL of Ampli Taq, and ddH₂O. The reactions were run in a thermocycler Eppendorf with an initial denaturation period of 1 minute at 95°C, followed by 40 cycles that included a denaturation period at 94°C for 1 minute, primer annealing at 58°C for 40 seconds, and extension at 72°C for 2 minutes; the cycles were followed with a final extension of 8 minutes at 72°C.

Digestion of the ITS fragment

Twelve restriction enzymes (*AluI*, *AvaII*, *BamHI*, *DpnII*, *HaeIII*, *HhaI*, *HindIII*, *HinfI*, *MspI*, *NdeI*, *RsaI*, *TaqI*) were tested to determine which would reveal variability. Three of these (*AvaII*, *HaeIII*, *MspI*) were selected for the subsequent analyses. PCR products were digested using 10 μ L amplified DNA, 1 μ L of each enzyme, and 1.2 μ L of buffer NEB2 for *HaeIII* and *MspI* and NEB 4 for *AvaII*. Digests were incubated overnight at 37°C, and then subjected to electrophoresis in a 3% TBE agarose gel.

Data analysis

PCR-RFLP is a dominant marker. Because of this, the variation of composite RFLP patterns of the ITS rDNA fragments generated by the enzymes was used to group into rDNA types. Genetic divergence between localities (island versus continent) was estimated with Fisher's Exact Test (Weir

& Cockerham 1984) using the program GENEPOP 3.1. (Raymond & Rousset 1995), and a cluster analysis based on Nei's genetic distance values (Nei 1978) was applied to estimate the genetic relationships, using the program TFPGA (Miller 1997). Intraspecies gene genealogies were inferred, using the median-joining network approach (Bandelt *et al.* 1999) as implemented in NETWORK 4.1.08.

RESULTS

Digestion of the ITS fragment (1400 bp) of *P. praeputialis* samples with the enzymes *AvaI*, *HaeIII*, and *MspI*, produced 11 restriction fragments with an average of 3.7 fragments per enzyme. Eight restriction patterns or types were observed, the enzyme *HaeIII* revealed the greatest diversity. Table 1 shows the frequencies, with the continental Brisbane and Barwon Heads localities presenting five types each; h5 was the most frequent type at both sites. A unique type was found at the Kingston site in Tasmania, which was absent from the continental sites.

Unsurprisingly, therefore, genetic differentiation was significant between the continental and island populations (Brisbane-Kingston $p < 0.001$; Barwon Heads-Kingston $p < 0.001$), with the pairwise comparisons including the Kingston site also showing the highest genetic distance values ($D = 0.788 \pm 0.09$). The two continental sites did not show significant genetic differentiation (Brisbane-Barwon Heads $p = 0.839$). The network analysis revealed a distribution in which a genetic type of major frequency was shared by both continental sites, with branches showing somewhat similar to "star shaped" diversity and another type unique to the Tasmania site (fig. 1). This differentiation pattern was observed in the cluster obtained from the hierarchical clustering analysis (fig. 1).

TABLE 1
Frequencies of the eight different types
of restriction fragment pattern

Type	Brisbane (n=11) ¹	Barwon Heads (n=9)	Kingston (n=6)
1	0.000	0.000	1.000
2	0.273	0.111	0.000
3	0.091	0.000	0.000
4	0.455	0.556	0.000
5	0.000	0.111	0.000
6	0.091	0.000	0.000
7	0.000	0.111	0.000
8	0.091	0.111	0.000

¹ number of individuals at each locality

DISCUSSION

A highly significant genetic differentiation was found between island and continental *P. praeputialis* individuals, with a fixed type characterising the Tasmanian samples.

The fact that we did not detect genetic types shared among the island and the mainland samples, could be explained either because the coasts are not connected today with no genetic flow, or perhaps because there are low frequencies of shared types but these were not evident in the sample examined, with this number of loci analysed. Both continental sites showed similar types and both differed from the Tasmanian sample. As a result of the isolation between the populations, and/or the limitations in the exchange of genes, is expected that the populations will diverge by genetic drift or selection for alleles that adapt to each population local niche. If a lack of gene flow exists at a sufficiently low level, then otherwise isolated populations will diverge genetically, and they will become disjointed and evolve as separated evolutionary units. However, genetic divergence among subpopulations resulting from random genetic drift could be prevented by low levels of migration.

The genetic flow is provided by the dispersal capacity of planktonic larval phases and this is related to the larval life span; for *P. praeputialis*, the free-swimming larval period is only two hours (Clarke *et al.* 1999), implying a reduced dispersal capacity. However, dispersal is also determined by the oceanographic characteristics of the occupied habitat (e.g., water masses and currents in Bass Strait) that facilitate or restrict larval dispersal. At present, the coasts of Tasmania are bathed by the Eastern Australian Current and, from the west, the Leeuwin Current. This should facilitate dispersal between the mainland and island coasts, as confirmed by the fact that Tasmania and the continent share fauna from the same biogeographic marine regions (the Peronian and Maugean zones) (O'Hara & Poore 2000, Waters & Roy 2003, Dawson 2005).

On the other hand, the sea squirt distribution could be explained by past events such as vicariant processes, reflecting the dynamics of the changes in the union and separation of Tasmania from the mainland, with repeated openings and closings of Bass Strait, and large temperature differences in the Plio-Pleistocene (Knox 1980). These have favoured genetic differentiation, allopatric divergence and possibly speciation in some species present on both coasts

(examples in Soh *et al.* 1998, Waters & Roy 2003, Waters *et al.* 2004, Colgan *et al.* 2005).

Alternatively, given the geological events discussed above, the extant population of *P. praeputialis* of Tasmania may have originated through past dispersal from continental *P. praeputialis* populations, with a series of geologic changes that occurred between the island and the continent facilitating the current breakdown in gene flow.

This scenario should be more fully evaluated in the future, by designing a population genetic analysis that includes taking more samples, covering more populations over a wider geographic range including eastern and western regions of southern Australia, and probably using molecular markers with greater variability.

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(accepted 6 October 2009)

H.M.S. BEAGLE IN TASMANIAN WATERS

by Peter Charles Stevenson

(with two text-figures, one plate and 11 tables)

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A photocopy of the log of H.M.S. *Beagle* from 1–22 February 1836 was examined and a transcription made from the handwritten script. The import of the column headings is explained, and comments are made on the course, navigation, the winds encountered, the weather, the sail handling, and the ship handling during the period at sea, and while in harbour in Hobart Town. An attempt was made to derive the synoptic weather situation.

Key Words: *Beagle*, FitzRoy, Darwin, Hobart Town, sail handling, ship handling, Charles Darwin.

INTRODUCTION

Between December 1831 and October 1836 H.M.S. *Beagle* made her second voyage to South America and around the world. The voyage was occasioned by the recent revolutions in the former Spanish colonies in South America which had opened them up to trade, and the British Admiralty wished to obtain accurate positions of safe anchorages on the inhospitable coasts.

The *Beagle* was a barque of 242 tons specially equipped for survey work, and unusually she carried 22 chronometers for the more accurate determination of longitude (FitzRoy 1839). On the recommendation of her commander, Captain Robert FitzRoy, and with the support of the Navy's Hydrographer, Admiral Francis Beaufort, she carried a naturalist to record the natural history of the parts visited. The naturalist was an inexperienced amateur in his early twenties, Charles Darwin, who paid for the passage of himself and his servants. Darwin (1839a, b) recorded his observations and, with special reference to Tasmania, his observations have been extended in Davies (2009).

MATERIALS AND METHODS

Photocopies of the log of H.M.S. *Beagle* were obtained from the Public Record Office, now The National Archives, Kew, in 2000. The *Beagle* log for the entire five years of the Second Voyage, when Charles Darwin was on board, appears in the records as ADM 53/236. The period covered by the copies examined here was 1–22 February 1836. The logs are handwritten and there is little variation in the script. The ship was commanded by Captain Robert FitzRoy R.N. and Charles Darwin was on board, but neither the captain nor Charles Darwin figure in the log. Four watch officers are identified, and the log appears to have been kept by Edward Chaffers, the Master.

DAY TABLES

General remarks

The Day Table is the unit of the log. Each covers 24 hours, is handwritten, and appears to be drawn up into columns with notations for each day. The handwriting does not appear to

change, as one might expect, and I interpret that the log was kept by the Master, Edward Chaffers. The Master usually kept a second copy of the log, and his copy has been used for the period 5–6–7 February. The handwriting is similar in this document.

The left-hand columns headed H, K and S are in accordance with Admiral Beaufort's "instructions" (FitzRoy 1839, pp. 32–42), and signify the Hour, the Speed in Knots, and possibly the state of the Sea, or the Swell. Enquiry of the Research Section of the Meteorological Office, Exeter, UK, elicited the response that they could not interpret this latter column heading.

The Course column which follows is indicated in compass points, there being 32 in the complete "Boxing of the Compass". Half points are used occasionally. The abbreviation "b" as in SbW indicates "by", and is given by a very small superscript "b". The Winds column uses the same compass conventions, and "Wly" indicates "Westerly".

There follows the Wind Force using Admiral Beaufort's Wind Scale, and the Weather column using the admiral's Weather Letters, and appearing in the "Hydrographer's Instructions" (FitzRoy 1839, pp. 40–41). There appears to be an added "a" to the letters, not recognised in the Instructions. The letter is quite clear and is often used, but close examination shows it must be "c". Moreover "a" never occurs with "c". The letter "q", indicating squalls appears often, though it can be confused with "g". Squalls were regarded with some fear, sometimes described by Captain FitzRoy as "pamperos" (FitzRoy 1839, pp. 85–89), and in view of the reputation amongst the crews of the Cherokee Class ships to which *Beagle* belonged, as a "Coffin Ship" (Geddie 1959), this was perhaps wise.

Then follows the Sympiesometer column. This early air barometer was preferred by Captain FitzRoy as being less fragile and handier than a mercury barometer, as well as affording an Air Temperature reading in Fahrenheit degrees as well as pressure. The Air Temperature had to be used as a correction before the air pressure could be determined. The figure given in the column is usually a decimal part of an inch, the whole number having been indicated earlier in the Day Tables. The Air Temperature follows. The next column poses a problem. The heading is very poorly written, but seems to be something like "Lee Sig". The column entries clearly are the initials of the Officer of the Watch, and appear two or three times in each 12-hour period. All of the initials have been recognised from the crew list.

Only four officers are involved in the records from Tasmanian waters: Peter Benson Stewart (PBS), the Mate; Edward Main Chaffers (EMC), the Master; Arthur Mellersh (AM), Midshipman and Mate from 1832; and, once, Charles Richard Johnson (CRJ), Mate.

Lastly follows the Remarks column. The ship's title is sometimes rendered "HMS" and sometimes as "H.M.S." Headed either AM or PM for the two halves of the day, the Remarks give details of the sail handling which are dealt with later in this paper. There are two Azimuth observations of the Sun on 21 and 22 February 1836, the first of the setting sun and the second of the rising sun. These observations use the Sun's declination for the day of the year and the ship's known latitude, where from Azimuth Tables the true bearing of the Sun can be derived (Norie 1943) — a very useful check on the magnetic compass in strange waters.

At midday on each page, a summary of progress is given including a consolidated Course and Distance covered, in Nautical Miles, a Dead Reckoning and Observed Position in Latitude and Longitude, in the form "143.53" not using degree and minute symbols. Then follows a Bearing and Distance to some prominent known point on the charts, presumably given from the midday fix, even though often the known point is not visible.

Thereafter the Day Table continues, without repeating the original column headings.

The log pages are in pairs, so that, for instance, 21 and 22 February appear on the same sheet. The day of the week is usually given, but 1836 does not always appear.

The positions of the Noon Sights are given in figure 1. All but two are astronomical, observed usually by extra-meridian altitudes of the Sun, giving both latitude and longitude; but overcast weather necessitates dead reckoning, using distances and directions from the last known position. There is no indication that the other methods of celestial navigation, ordered by the Hydrographer, were used (FitzRoy 1839). Where land is near, navigation is by land sights.

The names of sails are given in figure 2. Where the reading is not clear a query (?) is inserted. Transcription of the Day Tables is provided in tables 1–11, and an interpretation of each table is provided.

H.M.S. *Beagle* left Sydney on 30 January 1836 and on 1 February was making good steady progress down the East Coast of Tasmania before a northerly wind of force 6 (table 1). The wind was such that studdingsails were taken in during the early morning and the ship was making 8 knots. The morning weather was logged as "blue sky, cloud, mist" later changing to "overcast, cloud, mist, passing showers". A course alteration at 4 am was noted by Peter Benson Stewart. It was a warm day at 69 F° but cooling.

At midday only dead reckoning position was given, possibly due to the overcast sky, and a direction and distance given to Cape Pillar. The weather deteriorated further after noon, becoming gloomy, and the wind backed to northwesterly and strengthened, so reefing became necessary, force 10 being logged, and the sea state worsened temporarily. Later, however, the wind dropped to force 6–7, and by 8 pm the ship's speed had dropped to 6 knots, the sea state had reduced, but possible squalls were logged. Fore staysail and fore trysail were set and reefs cleared. By midnight, the ship was making 7 knots and the sea state was easy.

On 2 February, the wind was round to west-northwest by early morning, the weather was still gloomy but main and fore courses were set (table 2). At 5 am a remark was left incomplete, but by 7 am, reefs were shaken out with the wind at force 7, and at 10 am, royals and studdingsails were all set. The wind was dropping away but the sea state rising a little. Weather reported as "blue sky, cloud, good visibility". Land was seen at 9 am and again at noon.

The noon sight gave a dead reckoning and an observed position, and Cape Pillar was now 90 miles off. Peter Benson Stewart was the Officer of the Day.

The wind dropped to force 2 by afternoon and the speed to 4 knots. A course alteration towards the land was made at 2 pm, a ship was seen, spanker and gaff topsail were set to make good use of the slight wind, but soon reefs were put in and the jib and spanker taken in, possibly because the wind had gone round to the southwest. Towards evening, "blue sky, cloud, gloomy, and passing showers" were recorded. By 10 pm, the wind having dropped further, topgallants, jib and spanker were reset. The barometer was unsteady, the weather still gloomy and the sea state rising. About this

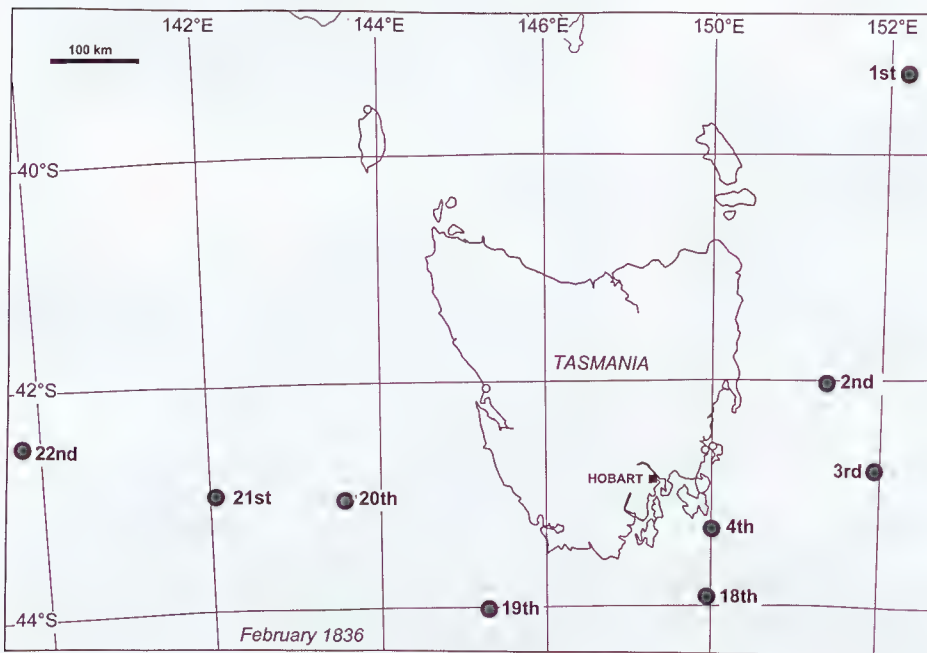


FIG. 1 — Positions of the noon sights

time, Charles Darwin complained that the weather was "very cold and squally" (Darwin 1839b, p. 532), but as a poor sailor this may have been an exaggeration.

On 3 February, the wind had veered to west by south at force 5, with "blue sky, overcast, (sic), gloomy, fog" (table 3). The course was now towards the southeast, then with failing wind, (force 2), to east by south. Reefs were taken out and the gaff topsail set. These were taken aback by a wind change and a risk of squalls; two reefs were taken in topsails, jib and spanker. The speed was now slow, 1–2 knots, and the wind variable. Wore ship, [by turning the ship through a large angle away from the wind instead of a small angle through the wind], to change tack, then set topgallants, jib and spanker, which were taken aback again in force 4 winds. Finally royals and flying jib were set, as if in defiance.

It must have been very trying. A detailed course can be constructed from the log, which shows that the ship was sailing north some of the time, but the inherent inaccuracies of this process show that an accurate plot is barely possible.

The noon position was given as 85 miles from Cape Pillar. The course was now southwest by south, a close-hauled course with the wind westerly. In force 2 winds studdingsails were set, but only to be taken in later with rising wind. Many course changes occurred in changing winds, but the wind was now veering to north northwest, and a course was taken to the southwest with spanker and gaff topsail set. The barometer was falling to 30 inches and below. Again Peter Benson Stewart was the Officer.

On 4 February, the sail was reduced and reefs put in as the ship was close-hauled five points off the wind (table 4). Jib and spanker, useful in this condition, were taken in and then reset. Topgallants were set and then taken in, but, with failing wind, reefs were taken out. Land was sighted; Cape Pillar, Tasman Head and Cape Raoul were identified and with the wind veering to north-northwest, royals and flying jib were set but soon struck. The weather was overcast and rainy with a hint of squalls.

There was no noon sight. In failing and variable wind, there were many course changes, with speed at 2 knots and continued fear of squalls. Tacking and a difficult work to windward occurred, with reefs to topsail, and main, jib and spanker struck. Bearings to Cape Pillar and Cape Raoul give running fixes, but rising wind split the fore topmast staysail and required the bending on of another. Anomalous half entries in the Signature column are of unknown significance. Again Peter Benson Stewart and briefly Charles Richardson Johnson were the signing Officers.

The description covering 5–7 February 1836 is taken from the Master's log (table 5).

With the wind northerly at force 6, and again with a hint of squalls, wore ship to change tack, and jib, spanker and topgallants were set. A running fix from the Capes was taken, and by 8 am reefs were taken out. The weather was overcast with some blue sky but gloomy, with squalls and passing showers. This day must be that referred to by Charles Darwin when he said that "the weather justified this awful name" of Storm Bay (Darwin 1839b, p. 532).

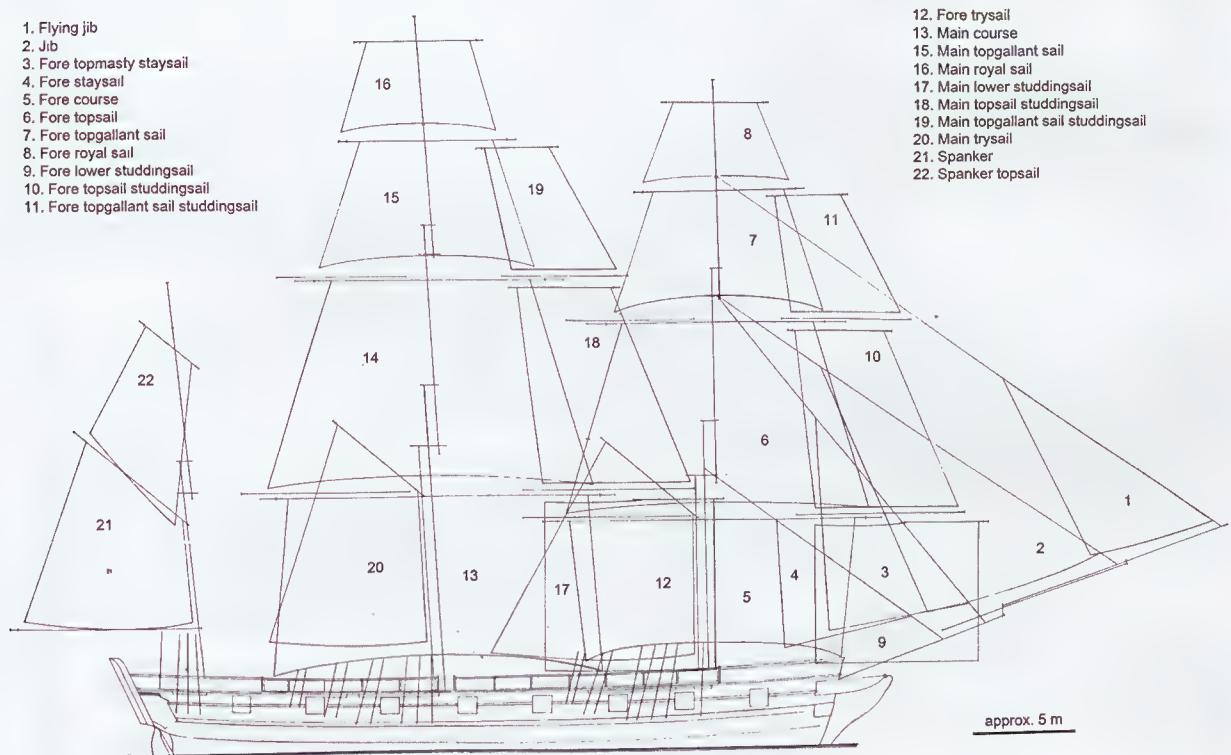


FIG. 2 — Sails carried on H.M.S. Beagle. (After Marquardt, K.H. 1997: *Anatomy of the Ship HMS Beagle Survey Ship Extraordinary*. Conway, Anova Books Ltd, London: 128 pp.)

17										Remarks. H. M. S. Beagle Feb 17th	
Hour	Course	Wind	Sea	Weather	Temp	Bar	Lat	Long	Remarks		
1											
2	Heard				50						
3											
4	Sp. T.										
5											
6	He	W. 1	by		05 10						
7											
8		SE by E 2	by		11 57						
9	Working out										
10	of the Drunken										
11	River	W. 2	by		14 57						
12											
										Bearings & Distance	
										Working out of the Drunken	
1	Working out										
2	of the Drunken	W. 4			18 10						
3											
4					17 58						
5	Steam by	SE 5			34 57						
6											
7	Sp	W. 4			40 55						
8	Sp										
9	Sp										
10	Sp										
11	Sp										
12	Sp										
										Remarks. H. M. S. Beagle Sunday 18th	
1											
2											
3											
4	W. South										
5	South										
6											
7											
8											
9											
10											
11											
12											
										Bearings & Distance	
										Riviera Rock S 82. W 9'	
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											

PLATE 1

Day Tables of 17 and 18 February 1836 in the log of H.M.S. Beagle. Reproduced with permission.

TABLE 1

Day Table of the log of H.M.S. Beagle for 1 February 1836

H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40-41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

H K S	Course	Wind	F	Weather	Symp	Atemp	L sig	Remarks HMS Beagle	Monday 1 st Feb
1 8 5	South							AM	
2 8 5	"	Nthly	6	b.c.m	.96	69			
3 8 3	"							2 In Course +TGt	Stdng sails + Royals
4 8 3	"								
5 8 2	SbW		-	-	.91	69		3.20 In Top (M)	Stdng sails
6 8 2	"	"	-	-					
7 8 2	"				.88	69			
8 8 5	"	"	-	-	.82	69		4 Altd Course to SbW	
9 8 5	"		-	o.c.m.p			PBS	(	
10 8 5	"	"	7	-	.78	67			
11 8 5	"								
12 9 -	"	"			.70	67			
Course	Dist	Latitude	Longitude	Bearing + Distance					
S(b)W	197	Dr	Obs	Dr	Obs				
		39.19		150.22		Cape Pillar S 10 W 220'			
1 8 6	SbW	9	o.c.g.m			PM 1.10 In Tgt sails 1 st + 2 nd reef Top sails			
2 8 -	-	10		.75	68	Furled Main sail in Flying Jib Boom			
3 8 -	-	NWly							
4 6 4	-	7							
5 8 -	-	5		.75	65	3.20 set rfs Main sail Main Trysail Jib and Tgt Sail			
6 6 5	-	6	o.c.g	.82	58	5 In TGT sail Jib and Main sail Clear rfs			
7 6 2									
8 6 2		7	b.c.q.g	.82	57	PBS Top sails + reef the Foresail down Tgt			
9 6 2						in 2 nd reef main topsails down fore trysails			
10 6 2	-	-	-	.90	59	6.15 set fore staysail + fore trysail rf			
11 7 2	-	-				9 out clear rfs of Topsails and reef of Foresail			
12 7 2	-	Nthly	6	b.c.g	.88	58			

TABLE 2

Day Table of the log of H.M.S. Beagle for 2 February 1836

H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40-41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

H K S	Course	Wind	F	Weather	Symp	Air	**	Remarks to HMS Beagle	Tuesday 2 nd
1 8 -	SbW								
2 8 -		WNW	7	b.c.g	.89	57		AM 2 up Main sails + up the Foresail	
3 7 -	-		8						
4 7 -	-	-	9	-	.90	57		5 set	
5 7 -	-		8						
6 7 -	-	-		-	.92	56			
7 7 4	-							7 out 3 rd rf of Topsails 8 crossed Tgt yds out rf	
8 7 4	-	-	7	-	.94	56		of Mainsl & Trysl, set Jib & Tgt sail 8.30 out	
9 7 -	-	-	-	-				2 nd rfs Obs land on W beam 9 out all rfs	
10 6 5	-	-	5	b.c.v	.92	56		10 set Starbd Top M Stdngsails 10.40 set Royals	
11 6 -	-							Flying & T.Gt Studding sails	
12 5 6	-	-	4	-	.88	56	PBS	12 Extremes of land WbS & WbS to S	
Course	Dist	Latitude	Longitude	Bearing and Distance					
S by W	169	Dr	Obs	Dr	Obs				
		41-56	42-01	149-11	149-21	Cape Pillar S45W dist 90'			
1 6 5	SW	NWly							
2 ½ 8	SWbS	NWly	2	b.c	.87	60		PM 2.15 altd course Trimmed sails set Spanker	
3 3 5	-							& gaff topl Obs a ship on lee beam standing to North	
4 4 -	-	-	2	b.c.g	.91	59		4.30 in Tgt sails and Gaff Topsl 1 st & 2 nd rfs of Topsls	
5 4 5	SEbS	SW	4	o.c.g.p					
6 4 -	-				.84	57		7.20 down Jib & Spanker in 1st rf Mainsails	
7 4 5	SE							10 set Tgt Sails Jib and Spanker	
8 4 5	-	-	6	b.c.g.p	.92	55	%		
9 4 5	-							11.30 in Ditto	
10 4 2	-	SSW	5	b.o.v	.94	55			
11 5 6	-								
12 5 5	-	-	-	b.o.g	.85	55	PBS		

TABLE 3
Day Table of the log of H.M.S. *Beagle* for 3 February 1836
H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40–41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

HK S	Course	Wind	F	Weather	Symp	Air	Sign	Remarks re HMS Beagle 3 rd Feb 1836
1 3 5	SEbS	WbS	5	b.o.g.f			/	AM
2 3 5	-	-	-	-	.18	57		
3 4 -	-	-	-	-				1 set Tg sails Jib + spanker
4 3 5	-	-	4	b.o.g	.20	51		2 in Do. to a squall 2.30 set Do.
5 3 -	SE	-	-	-				5 out reefs of Main Sl and reefs of Top Sl's +set
6 1 2	EbS	-	2	-				
7 1 5	**	-	-	-				
	SbE	-	-	o.c.q	.20	54		Gaff TopSl 5.30 Tacked 5 Taken aback with the wind from the SW Trimmed on Starbd tack in T.Gt sails 1 st and 2 nd reefs of TopSails Jib and Spanker
8 3 2	SWbW?	Vble	-	o.c.q.p	.24	53		
2 4	**	-	-	-				
9 1 2	SWbS	-	-	-				
10 1 2	-	-	-	-				
4	NW	-	4	b.c.g?	.22	56		6.15 Wore 7 set TGT Sails Jib and Spanker
11 1 -	NNW	-	-	-				8. out all rfs 8.40 Tacked 9.15 Taken aback
12 2 -	SSW	-	-	-				10.15 Tacked set Royals and Flying Jib
4	-	-	-	-	.22	56		Cape Pillar S74W 85
Course	Dist	Latitude		Longitude		Bearing and Distance		
		Dr	Obs	Dr	Obs			
S16E	57	42.55	42.48	149.53	149.56	Cape Pillar S74°W 85 miles		
1 4 2	SWbS	Wly?	-	-				PM
2 2 5	-	-	2	b.c	.15	56		3.30 Trimmed set Strbd Topmast
3 2 5	SW	-	-	-				
4 3 6	WSW	-	4	-	.08	58	PBS	and T.Gt Studdingsails
5 7 -	SWbW	-	-	-				5.20 in TGT Studding Sails and trimmed
6 7 8	-	-	-	-	.12	58		
7 8 -	-	-	-	-				6.30 down F Top Staysails + Trysails
				29	10	Coarse?		
8 7 4	-	NbE	5	b.c.g	.84	58		
9 3 7	-	-	-	-				
3 8	WSW	-	-	-				10 Trimmed Sails in Top M. Studding Sails
10 5 5	-	-	2	b.c	.76	60		set Spanker and Gaff Top Sail
11 3 5	SW	NNW	-	-				
12 3 5	-	-	-	-	.71	60	100	

There was no noon sight as land was close, and the rest of the day was given as “working up Storm Bay and standing up the Derwent”. The lighthouse at the Iron Pot was noted at 2.20 pm.

Wind was variable, and short sail was made “as requisite to squalls”. Such sharp capfuls of wind are very common in summer as the air drains off Mount Wellington, and to this day catches ships, large and small, unawares.

Sullivans Cove was entered at 6.40 pm, and mooring was completed with 30 fathoms of cable from bow and stern. H.M.S. *Beagle* was moored in the cove but not laid alongside, there being no established wharf. The expression “B.B.” appears, and is taken to mean Best Bower, the starboard bower anchor and the best anchor in the ship.

The next days, from 6–16 February, potentially were of great interest, since they are the days when Charles Darwin was recording his important observations concerning Tasmania (Davies 2009). However, the log entries record only the merest outline of activities such as “harbour duties”, or “employed variously on ship’s duties”. On nearly every day the entry “received 69 lb of fresh beef and veg.” appears and one may speculate why this particular quantity was delivered each day. “Wood” is given on one day, presumably as fuel for the Cook. On Sunday 14 February at 10 am the crew was “mustered by divisions”, for Divine Service, but at 5 pm the topgallant yards were lowered; the work of the ship had to go on. On this day also, Darwin wrote to his sister Catherine to the effect that, “there never was a ship

so full of homesick heroes as the *Beagle*” (Darwin 1836).

On Monday 15 February, the topgallant masts were re-erected and the yards “crossed” on the following day. On this same day, 16 February 1836, Lieutenant Duff of the 21st Regt. was embarked “for passage to England”.

It is noteworthy that the Wind, Force, Weather, Sympiesometer, and Air Temperature readings were scrupulously observed for every day in harbour. The value of this information as a predictor of the future was probably in the captain’s mind.

The 17 February 1836 began with the reception of 207 lb of fresh beef and “vegls”. The ship was then hove short on B.B., the Best Bower anchor. At 9 am anchor was weighed and all sail made to royals. The weather was still gloomy. The wind was variable and force 1, and later, towards noon, passing showers fell. The wind was now northwesterly and variable, not atypical for Hobart. After noon (no sight), the ship was tacking in rising wind which was now southeasterly but still variable, required lowering royals and topgallants, first and second reefs were taken in topsails. The Iron Pot Lighthouse was passed at 2 pm, and reefs were taken out in failing wind. The course was now southeast and a bearing was made of Cape Raoul. At 11.15 pm the courses (main sails on both masts) were set and try sails taken in. The land was lost at 10.30 pm in the darkness, the ship having made 20 miles or so to the seaward. Arthur Mellersh, Peter Benson Stewart and Edward Chaffers were the Officers (table 6, pl. 1).

TABLE 4
Day Table of the log of H.M.S. *Beagle* for 4 February 1836

H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40–41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

HK S	Course	Winds	F	Weather	Symp	Air	Sig	Remarks HMS Beagle Thursday 4 th
1 4 -	SWbW							AM 12.40 in Royals and F. Jib
2 4 4	"	WNW	5	b.c.g	.67	57		1 in TGt Sails 1 st + 2 nd Reefs of Topsails
3 3 -								set F. Trysail 2.45 in Jib and Spanker
4 4 -	"	"	"		.65	58	PBS	
5 4 -								saw the land NWbW set Jib and Spanker
6 4 -	"	"	"	o.c.g.p	.64	58		+ TGt Sails 4.30 In TGt Sls
7 3 5	WSW							
8 4 5	"	"	4	b.o.g	.66	56		6.50 out 2 nd rfs + set TGt sails + Gaff Topsail
9 4 7	SWbW	"	5					Cape Pillar NWbW Tasman Head N9W
105	NbW	"	4	"	.64	56		Cape Raoul N56W 9 Tkd.
114 3	NNW							11.30 set Royals + Flying Jib 12 in Do.
123 5				2 o.c.w.q.p	.65	57		
Course	Dist	Latitude	Longitude	Bearing and Distance				
		Dr	Obs	Dr	Obs			
1 1 5	West					PM		
2	SW Vble							
2 2 2		4	b.c.g.p	29.64	56	1.30 Tacked	in 2 nd reef of Topsails	
2 5	NW							
3 4 5	"					1.50 out Do.	3.30 Tacked Shortened	
2 4								
4 3 2	SSW Westly							
5 2 5	South	5	--"	.62	56	CRJ	Sail as requisite to squalls	
3	NWbW							
6 4 8	NW	"	--"	.64	56	PBS	4.30 tacked 6 tacked in Top Gallts	
7	Working to Windward							
8 1 8	SSW						+2 nd reef of topsails + 1 st of M. Sail Down Jib + Spanker	
9 2 8	SW WNW							
102	"	"	b.c.q	.74	50	½	6 Cape Pillar N51E Cape Raoul N80W	
113 2	"	"				½	8 Cape Pillar N34E 9 Split the F.T. Mast Staysl unbent + bent another	
123 6	"	6	b.c.q	.72	50	½	12 Cape Pillar SSW ¼ m Cape Raoul N ½ W Tasman Hd WbS ½ s?	

On 18 February, the ship was becalmed at 2 am, but the course was laid south before a fitful northerly and rising wind to become south by west by 7 am. All sail was made including studdingsails, and trimmed, and the course maintained, making 5–6 knots (table 7, pl. 1).

The noon sight gave a position and a bearing to an unidentified "Ruisck Rock", but the position suggests that this was Pedra Branca, 23 km off South East Cape. With the wind rising to 6, the studdingsails were struck. The course was now west by south before a light northerly wind. Land was seen northwest by west to north northwest. There is high ground in Southwest Tasmania, and this would be visible at a distance of perhaps 50 miles. At 7.15 pm "Peak to Sugar Loaf N25W" is recorded. A rough plot using known positions and recorded distances through the water shows this bearing passes through Federation Peak, a prominent point at 1224 m. With the wind still light, studdingsails, royals and flying jib were set, the *Beagle* was making 5 knots, the course being still west by south.

On 19 February the course was maintained west by south, the wind was still light and variable from north to east. All day the sails were set and trimmed to try to get more speed. The weather was overcast, with rain and mist, and a noon sight was not possible, but a position was given by dead reckoning, estimating South West Cape S56W at 52 miles (table 8). This must surely be a mistake, as this would put the ship somewhere in the mountains of Western Tasmania. If the reciprocal bearing of N56E is accepted,

then this puts the ship very close to the dead reckoning position. This mistake would hardly mean anything to the navigator on the ship, but looks very strange to a subsequent historian. The consolidated Course of S89W and the Day's Run confirm the true position.

In the afternoon, the course changed round as far as east with continuing dull rainy weather, but rising wind, to force 7, required reefs to be put in, and the striking of royals. By 7 pm the wind had gone to south so a course west by north was laid. A rising barometer was recorded.

By 20 February, southeast and variable winds enabled a course approximately northwest to be maintained and reefs were taken out in force 4 wind. Changing winds to northwesterly made tacking necessary, not usual at sea. A noon sight gave a position, with Point Hibbs estimated at N72E 105 miles. The course was changed to south-southwest in the face of northerly winds (table 9).

In the afternoon the wind at force 4 became squally, reefs were taken in topsails, and the weather remained gloomy and rainy, but the wind going to south-southwest made the sea state change to rough for a time.

With the wind from south-southwest on 21 February and the course nearly four points off at west by north, reefs were taken out and royals and flying jib were set. Even in light winds, 3–5 knots was attained at times. Mustering for Divine Service did not prevent the wind dropping to force 1–2 and variable, and a noon sight gave a position and a distance of 188 miles from Kings (sic) Island of 188 miles (table 10).

TABLE 5

Day Table of the log of H.M.S. *Beagle* for 5, 6 and 7 February 1836 derived from the second copy of the log kept by the Master, Edward Chaffers

H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40-41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

HK S	Course	Wind	F	Weather	Remarks to HMS Beagle Feby 5 -6-7-1836	
1 3 5	SW?					
2 3 5	NNW?	Nthly	6	o.c.q	AM 1 Wore ship	
3 4 5					4. Cape Pillar NEb½E & Cape Raoul NNE½E	
4						
5						
6		"		b.c.g	4.40 set Jib Spanker + Top Gallt Sails	
7						
8	Working				8. Tkd out 2 nd rfs of Top Sails Quoin R*	
9	up					
10						
11	Storm Bay	"		b.c.q.p	NNW 2'	
12					Tkd as reqte Working up Storm Bay	
Course	Dist	Latitude		Longitude		Bearing and Distance
		DR	Obs	DR	Obs	
"	"	"	"	"	"	Working up Storm Bay
1	Working up Storm					PM Tkd occasionally Working up Storm Bay
2	Bay	West?	5	b.c.q.p		2.20 Pass'd the Light house
3	&					
4	Standing up the	Vble	4	c.p		Made + Short Sails as reqte to squalls
5	Derwent					Standing up the Derwent + working up to Sulivans
6						
7						Cove 6.40 Short Sail + came to in 10 fams
8	Moored in Sulivans					with B.B. Furled sails + moored ship 30 fams
9						
10	Cove		1.	c.p		each way
11						
12	Hobart Town		4	"		
		Nthly	2	b.c		AM 6th
						6.0 Cu*** + loosed sails
Moored						
Off						
Hobart		Vble	"	"		10 Furled sails Received 69 lb Fresh Beef +
Town						vegetable
		Sthly	4	b.c.q..p		PM
						Empd as requisite

TABLE 6

Day Table of the log of H.M.S. *Beagle* for 17 February 1836

H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40-41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

HK S	Course	Wind	F	Weather	Symp	T air	Sig	Remarks H.M.S. Beagle Feby 17 th
1								
2								AM
3	Moored				30			Received 207 lb of Fresh Beef+ vegls
4								Trimmed ? + hove short on B.B.
5	Sngl ?	↓Vble	1	b.m.g	.05	60		9 Weighed and made all sail to Royals
6								
7	Sh?							
8								
9	NWly	2	c.g.p	.11	59½			Tacked Trimmed made and shortnd sail as reqte working out of Derwent River
10	Working out							
11	of the Derwent							
12	River	Vble	2	b.c.g.m	.14	59		
Bearings and Distance								
Working out of the Derwent								
1	Working out		1	o.c.g.p				PM Tkd as reqte working out of the
2	of the Derwent	Vble	4	"	.18	60		
3	+							Derwent 2. Passed Iron Pot Light house
4				b.c.g	.17	58	AM	2.30 g? in Royals + Tgt Sails 1 st +2 nd rfs of
5	Storm Bay							
6		SEly	5	"	.34	57	PBS	Topsails 3 out reefs set TGt Pts? + Tkd
7								
8 6	SE	Vble	4	b.c	.40	55	EMC	6.0? Cape Raoul E (b?) S 1½'
9 6	SE							10.30 Lost sight of the Land
10 5	ES	"	2	"	.40	55		
11 3								11.15 up Courses + down Trysails
12 1	ENE	"	1	"	.38	55	AM	

TABLE 7
Day Table of the log of H.M.S. Beagle for 18 February 1836
H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40-41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

HKS	Course	Winds	F	Weather	Symp	Air	Remarks
1				o.b			
2		Ø	Calm	0	.36	57	AM
3	Ato S						
4		Nthly	1	b	.33	57	daylight saw the Land Brg NW
5 2	South						
6 3		"	2				
7 2 4	SbW			"	.38	56½	Trimmed + made all sail with Studdingsails
8 3		"	4	"	.40	57EMC	
9 4 5		"					
10 5		"	"	"	.40	55	11. set Starbd Fore Lower + Std Lwr Top Gt
116 "				o.c.m			Studding Sails
126 6		NE	"	"	.31	58	AM
Course	Dist	Latitude		Longitude		Bearing + Distance	
		DR	Obs	DR	Obs		
---	---	43.58	43.58	148.05	147.58	Ruisck ? Rock S 82 W 9°	
1 7 5	SbW					PM	
2 6 5	WbS	North	6	b.c.m	.26	56	In Port Studng Sails + Starbd TGt Do. Trimmed
3 9 2	"						
4 9 .	"	"	"	"	.21	58	PBS + Alto Co to WbS set Stbd Fore Top Lwr. Studg
5 9 .	"	"	5	b.c.m.g			Sails + Jibs 2. In Royals Flying
6 8 6	"	"	2	"	.16	57	Jib + M Top Stb? Stud Sl 3 in Fore Top Gt Do.
7 7 6	"	"					5.10 saw the Land Brg NW
8 7 .	"	"	2	"	.10	58	AM 6 Land from NWbW to NNW 7.15 Peak t Sugar
9 6 "	"	"					Loaf N 25 W
106 5	"	"	2	"	.04	68	set Fore Top Mts? Studng Sail Royals + Flying Jib
114.					29		
123 .	"	"	"	"	.98	59	

TABLE 8
Day Table of the log of H.M.S. Beagle for 19 February 1836
H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40-41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

HKS	Course	Winds	F	Weather	Symp	Air	Sig	Remarks re HMS Beagle Friday Feb 19 th
1 4 .	WbS	Nrthly			29.			
2 4 .	"		2	o.g.d	.92	57		AM in Fore Top Mast Studding Sail Royals
3 2 .								+ Flying Jib 2. Trimmed 3.20 Trimmed +
4 2 .	"	NWly	"	o.n?	.90	50EMC		made all sail on Strbd Tack. Daylight
5 1	"	Vble	1					
6 1 5	"	Ely	2	o.c.r.m	.90	58		saw the Land Bg N½W to NNE
7 3 2	"	"	4	o.g.m				set Royals Flying Jib Stbd Top M+TGt Stuns
8 5 2	"	NbE	"	"	.92	58	AM	
9 4 "	"							set Fore Trysail
103 5	"	NEly	2	o.d	.86	57		9.45 Trimmed + set Stbd Lower Studding Sail
113 6								
124 "	"	"	4	o.r	.87	59	PBS	
Course	Dist	Latitude		Longitude		Bearing & Distance		
		DR	Obs	DR	Obs			
S 89°W	119'	44.07		145.14		SW Cape S 56 W 52'		
1 1 .	WbS							
2 " 8	West	North	1	o.c.p	.86	57	PM	
3 " 8	WSW					1 Altd Course to West 3.10 braced round to Port		
4 2 8	East	"	4	"	.86	56½		
5 7 "	"					4.40 In Royals + Flying Jib		
6 7 4	"		5	o.c.m.p.g	.95	52	AM	
7 8 8	"	South					PBS	
8 5 4						5.20 In 1 st + 2 nd rfs of Top Sails+reef of Mn Sail		
-----		"	7	o.c.m	.98	52		
3	WbN?					+ 1 st of Spanker		
9 8 "	"				30			
106 8	"	"	6	b.*	.06	53		
116 "						9.30 Trimmed		
126 "	"	"	5	o.c.g	.08	53EMC		

TABLE 9

Day Table of the log of H.M.S. *Beagle* for 20 February 1836

H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40-41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

HK S	Course	Winds	F	Weather	Symp	Air	Sig	Remarks re H.M.S. <i>Beagle</i> Saturday 20 th
1 5 8	WNW	SE						
2 4 8	NWbW		5	o.c.g	.08	52		AM
3 4 5	NW	Vble						
4 4 "	"	"	"	"	.08	52	AM	6 out 2 nd rf of Main Sail
5 5 "	NWbW	"						
6 5 4	"	"	4	"	.08	54		10 out 1 st reefs of Top Sails
7 5 "								
8 5 7	" N?NW	"	"	"	.10	54		10.20 Tacked
9 6 "	NNW							
105 8	N½W	"	"	"	.12	55		
2	North							
115 2	SSW	"						
125 "	SbW½W			b.a.p.g	.10	55		
Course	Dist	Latitude	DR	Obs	Longitude	DR	Obs	Bearing + Distance
N67W	110	43.23	43.03		142.55	143.35	Est?	Pt Hibbs N 72° E 105'
1 4 8	SWbS							PM
2 4 5	"	NE?	4	o.c.q	.10	54		
3 4 "	"							
4 4 "	"	"	4	o.g.q	.07	54	AM	
5 5 "	"							
6 5 "	"	"	"	"	.08	54		in 1 st reefs of Top Sails
7 4								6.45 Tacked
1 "	West							
8 4 2	"	"	4	o.g.q.p	.14	54		
9 3 5	"							
103 8	WbN	SSW	4	"	.15	57		
114 4	"			b.c.p				
125	"	"	"	b.c	.20	57	AM	

TABLE 10

Day Table of the log of H.M.S. *Beagle* for 21 February 1836

H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40-41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

HK S	Course	Winds	F	Weather	Symp	Air T	Sig	Remarks re HMS <i>Beagle</i> Sunday Feb 21 st 1836
1 5 "	WbN	SSW	4	b.c?	.16	52		AM
2 5 "	"							
3 5 "	"							2. out 1 st reefs
4 5 2	"	"	"	"	.19	52		
5 5 "	"							6. set Royals + Flying Jib
6 4								
1	WbS				.28	51		
7 4 5	"							
8 5 "	West	"	2	"	.32	67?	EMC	10.20 Mustered by Divisions
9 3 5	NbW							
103 5	WNW	Vble	"	"	.32	51		
113 3	"							
122 5	"	"	1	o.c	.3251		AM	
Course	Dist	Latitude	DR	Obs	Longitude	DR	Obs	Bearing + Distance
N 88 W	86'	43.00	42.55		141.37	142.03	**	Kings Is. Strd? N 25 E 188'
1 1 8	West	SSW						PM
2 3 "	WbN	Vble	2	b.c	.32	51		
3 2 "	"							
4 1 7	West	"	1	"	.3252		PBS	
5 1 7								
6 2 "	"	"	"	"	.43	55		7. (o) set S 56°50' W
7 2 "	"	SSE						7.15 Trimmed + set Port TGt Studd Sl*?
8 2 8	"	"	2	"	.34	52	AM	Fore Top Mast Studding Sails down F Trysail
9 2 5	"							9.30 Trimmed down Trysails + Spanker
102 5	"	"	1	"	.30	53		set Fore Course + Top mast Studding Sl's
112 "	"							down Jib
122 2	"	SEly	"	"	.30	53		

TABLE 11
Day Table of the log of H.M.S. Beagle for 22 February 1836
H = Hour; K = Speed in Knots; S = ? State of the sea or Swell; Course, measured in compass points, there being 32 in the complete "Boxing of the Compass"; b = by; Wly = westerly; Wind Force measured by Admiral Beaufort's Scale; Weather, recorded as Beaufort's weather Letters in FitzRoy 1839, pp. 40–41; q = squalls; Sympiesometer = barometric pressure; Air Temperature in degrees Fahrenheit; Lee Sig = ? initials of the Officer of the Watch.

HKS	Course	Winds	F	Weather	SympThrm	AirSig	Remarks re HMS Beagle Monday 22 nd
1 3	“ West						
2 3 4	“ Eastly	2		b.	.32	51	AM
3 3	“						3. Trimmed Sails
4 3	“	“	“	“	.3251	EMC	5.35 (o) rose S 83°E
5 3 8	“						
6 4 5	“	“	2	“	.37	51?	6.20 set Stbd Fore Course + Stbd? Top Mst
7 4 5	“						Studng Sails up Mn Sail
8 4 7	“	“		“b.c	.41	52	AM 9.30 Shifted ? over Studding Sails
9 5 8	“						
106	“	“	4	“	.37	54	
116 6	“						
126 8	“ ENE	4		“	.34	54	PBS
Course		Dist	Latitude		Longitude		Bearing + Distance
			DR	Obs	DR	Obs	
W 81	81		42.40	42.29	139.53	139.48	Kings Is. Str? N51 E – 230'
1 6 8	West						PM
2 7 5	“ ENE	4		b.c	.30	55	
3 8	“						
4 7 5	“	“	4	“	.29	55	
5 7 5	“						7.30 Carried away Stbd Main Top Mt.
6 7 6	“	“	“	“	.26	54	AM Studg Sail Boom In all Studding Sails
7 8 8	“						
8 9 2	“	“	7	b.c.m	.18	55	PBS + Royals
9 8 4	“						
108	“			“	.22	55	9 Trimmed
118 5	“						
128 3	“	“	5	o.g.m	.11	55	EMC

At 7 pm an Amplitude observation of the sunset gave a true bearing of S56°50W to enable magnetic bearings to be corrected. Winds remained light but southeasterly and sail changes tried to get the best out of force 1 and 2. The weather was clearer with blue sky and clouds.

A course to the west was held on 22 February with winds easterly and slowly rising. The weather remained fair (table 11). Another Amplitude observation of sunrise gave a true bearing of S 83°E. Sails were set in force 2–4 winds. A noon sight gave a position and a distance from King Island of 230 miles at N51E. At 7.30 pm rising wind carried away the starboard main topmast studdingsail boom, prompting all studdingsails and royals to be struck and the ship was now making 7 or 8 knots with a following wind.

DISCUSSION

From these interpreted remarks, one is constantly made aware of the complete reliance of the voyage on the wind and the weather, and the constant demands of the crew to go aloft night and day to handle the sails. There is a sense that the crew was trying to hurry the ship along, but taking care to respond carefully to squalls.

Sail handling

Sail handling on such a vessel as *Beagle* is very much the creature of the wind and intended course directions. It is instructive to compare these two directions on a compass rose (a circular diagram representing the 32 “compass” points radially). This reveals the extent to which the ship is “close-

hauled”, that is, how much she is made to sail into the wind. The changes made to the rig before the ship left England, namely the addition of a mizzen mast and a spanker sail enabled her, together with the carrying of inner and outer jibs and staysails, to be sailed to some extent as a “fore and aft” vessel. She would then be able to sail closer to the wind and be more controllable in difficult conditions. The fore and aft sails would also require much less manpower and would also be safer, as the crew would not need to go aloft, as square sails would require.

The urgency of the return to England is evident from the frequent use of studdingsails, additional sails set out on either side of the square sails. Just a few more miles in the day made the extra effort and risk worthwhile. At the same time prudent first and second reefs are taken, it is not worth taking too much risk and losing the ship towards the end of the voyage.

For example, on 3 February 1836 at 5 am the ship was taken aback, that is, a change of wind fell on the forward sides of the square sails, a distressing situation. A course change gave some relief, and ultimately wearing ship, that is, changing tack by turning away from the wind, did not prevent it happening again at 9.15 am. Finally the wind resolved itself and serene sailing resumed. By the afternoon, staysails, trysails, and spanker and gaff topsails were all in use, that is, all fore and aft sails.

Late on 4 February, in the dark, when south of capes Raoul and Pillar, the fore topmast staysail was blown out and had to be replaced. After more than four years at sea, it is unlikely that any sails were new.

The weather situation

The weather during the Tasmanian part of the voyage is given in the Meteorological Observations in Volume II of FitzRoy (1839). The entries correspond well, but there is more immediate detail in the log.

Ian Barnes-Keoghan of the Hobart Office of the Bureau of Meteorology (pers. comm.) comments as follows: "6–17 February 1836, Hobart Town

The reported weather through this time seems not atypical of a Hobart February: temperature in the (degrees Celsius) teens, generally "fine" weather, but with a cold front.

On Beagle's arrival in Hobart, the winds are light and variable, weather clear (though with some cloud), and the pressure moderately high (as would be expected with a high pressure system nearby), temperature 10 or 11°C (although these are mostly taken at 9 am, so such low temperatures are reasonable).

There appears to have been a cold front crossing between 4 pm and 9 pm on 14 February. The 4 pm temperature was 24°C, with the wind strengthening (and squally) north to northwesterly (it reaches force 7), and the barometer falling steadily. By 9 pm the wind has shifted southeasterly, and lightning is reported. The next morning finds the temperature around 13°C and the weather "gloomy". The reports do not make any mention of rain during the period, although it is possible this fell at other than an observation time."

An examination of the weather reports of the entire 22 days of the record enables some other comments to be made. The abrupt change of temperature, the squall indication, the "gloomy" remark, and reefing at 5 pm on 1 February seem to indicate the passage of a cold front. High barometer and more "gloomy" comments on the following day may represent a summer-time high, as does the change of wind to the south-southwest.

Variable winds on 3 February, which require some complex manoeuvres attended by squalls, precede the re-establishment of northerly winds late in the day. On 4 February blue skies and at the same time overcast and gloomy weather are recorded, and may perhaps indicate mountain waves in the wake of the Tasmanian mountains. Squally weather on 5 February may be indicative of the sudden gusts experienced close to the Tasmanian mountain coasts.

Taking up the story on 17 February, light northerly winds and a change to southeasterly hampered progress to the seaward from the Derwent, and on 18 February a calm sea presaged a rising northerly, accompanied by a falling barometer. This continued to fall on 19 February with variable and easterly winds, enabling quicker progress to be made at the end of the day. A late rise in the glass and another change of wind from east to north and then south must have made the crew wish for the open sea and more consistent winds.

This wish was not fulfilled on 20 or 21 February with more continuing light and variable winds, squalls again indicated, and the ship clawing to the northward. But on 22 February the easterlies improved, and better progress was made, even to the extent that a studdingsail boom was carried away as the ship set course for King George's Sound in Western Australia.

There appears from the density of weather information that synoptic situations could be derived from it, but this remains to be attempted.

An unanswered question

While in Hobart, Captain FitzRoy wrote (FitzRoy 1839, p. 624):

"During a few days stay in Sullivans Cove, the chief anchorage, we had opportunities of going some distance into the country, and seeing things which led me to think that there is a more solid foundation for future prosperity in Van Dieman's Land than can be found in Sydney. Natural advantages are greater; and likely to increase as the land is cleared and inhabited — because rain is now almost too plentiful, though corn ripens well and is of excellent quality."

David Leaman (per. comm.), who has followed Darwin's movements in Tasmania very closely (Banks & Leaman 1999), notes that Darwin was appointed to be companion to FitzRoy and speculates that during the second week of their stay, Darwin was free to do much as he liked and was not required to attend dinner with the captain. Indeed, he came in late, or ate out. These actions may mark the days of FitzRoy's absence. Given the few comments made by FitzRoy about midland Tasmania and his aristocratic connections it seems likely that he visited, or was invited to stay with, the local members of upper class Tasmania in the region between Connorsville and Fingal in northern Tasmania.

Where did he go, and who did he see? My enquiries have revealed no answer so far.

ACKNOWLEDGEMENTS

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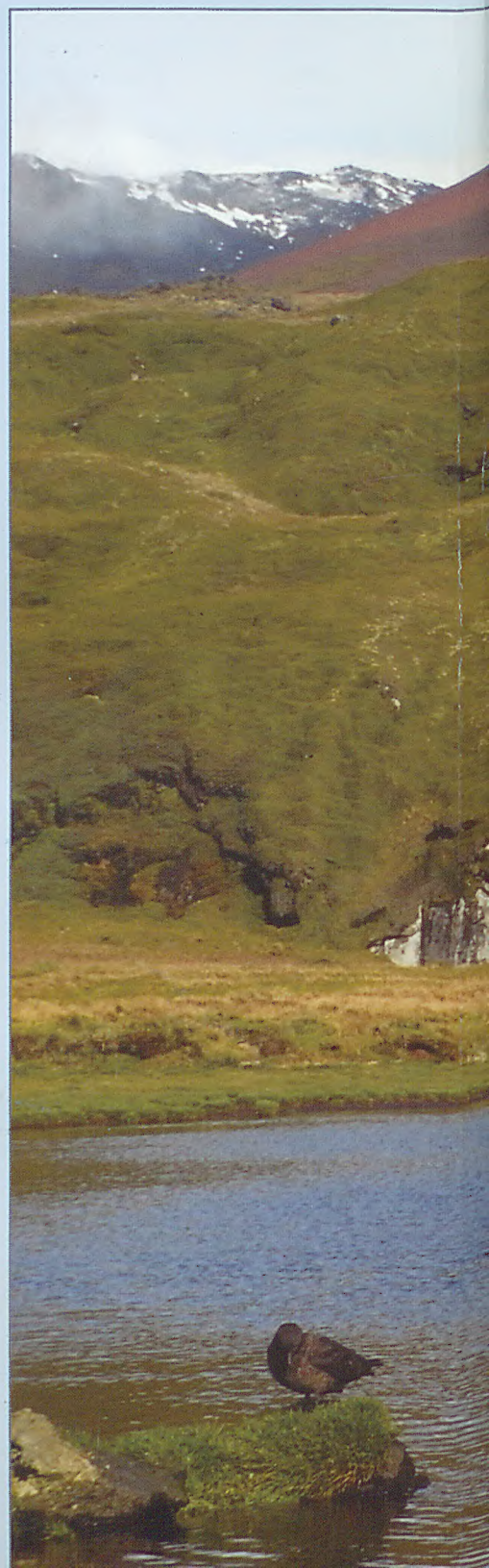
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